Atrai: A Framework for Rapidly Implementing Programming Languages

Lecture 9

Programming Language/DSL: Implementation Steps

- Write a parser for the language
- Parse a program to generate a simple form of the parse tree called Untyped Tree
- Write a program that interprets the Untyped Tree
  - Specify a Transformer that describes a set of rules on how to transform an untyped tree into another
  - Transformers can quickly encode the operational semantics rules/type checking rules/code generation rules

Write Grammar in ANTLR 4

- Avoid using Kleene *, +, ? for binary operators
- Left recursion is allowed
- Uses ALL(*) algorithm [out of scope of this class]
- ANTLR resolves ambiguities in favor of the alternative given first
  - allows to specify operator precedence implicitly
  - ANTLR associates operators left to right as we'd expect for * and +
  - right associativity is specified manually using <assoc=right> option

Sample Grammar in ANTLR 4

```
grammar Ex;                                          // generates class ExParser
stat: stat expr ';'
            | expr ';'
            ;
expr: <assoc=right> expr '^' expr
            | expr '*' expr
            | expr '+' expr
            |  '(' expr ')'
            | num
            ;
num: INT;
INT: [0-9]+;
WS : [ \t\r\n]+ -> skip ;                            // ignore whitespace
```

Environment API

- Simple and INEFFECIENT implementation

See javadocs/index.html for documentation
See src/main/java/atrai/interpreters/common/Environment.java

```
public class Environment {

  public static Environment extend(String key, Object value, Environment env);

  public Object get(String key);

}
```

Environment Implementation

- Simple and INEFFECIENT implementation

```
public class Environment {
    private final String key;
    private final Environment next;
    private Object val;

    private Environment(String key,
            Object val, Environment next) {
        this.key = key;
        this.val = val;
        this.next = next;
    }

    public static Environment extend(String key,
            Object value, Environment env) {
        return new Environment(key, value, env);
    }

    public Object get(String key) {
        Environment tmp = this;
        while (tmp != null) {
            if (key.equals(tmp.key)) {
                return tmp.val;
            }
            tmp = tmp.next;
        }
        return null;
    }
}
```

Atrai (After the name of a river in north West Bengal)

- A framework for matching and transforming trees
- Written in Java
- Uses three basic concepts
  - Untyped Tree
  - Pattern
  - Template
- Advanced concepts: Transformer and Visitor
- PA2 will use Atrai for rapid prototyping

Installation and Running Interpreters

Inside Atrai directory execute to build Atrai and run tests:

```
mvn clean test
```

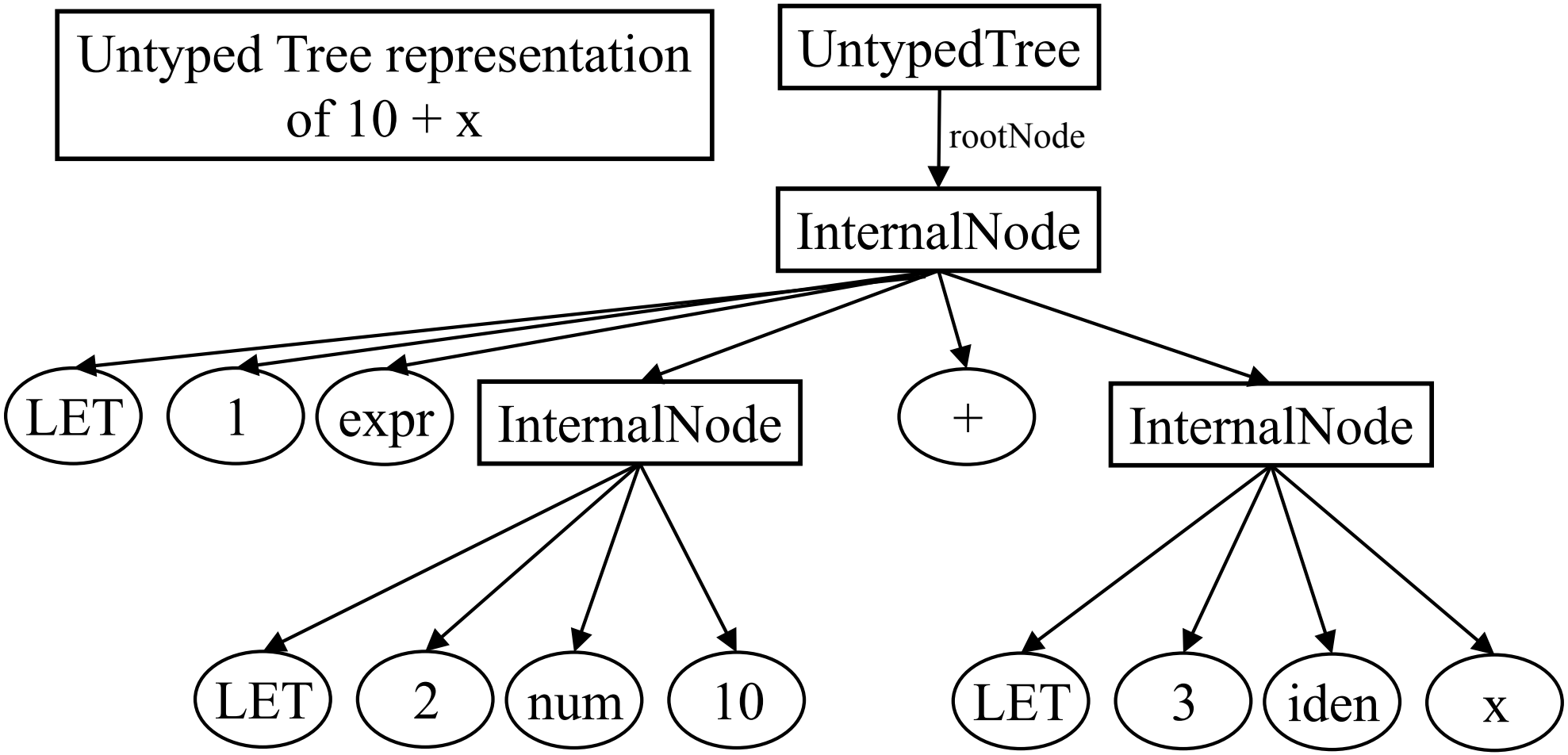
To run the LET interpreter on a sample LET program, say test.let, execute

```
mvn clean package
java -jar lib/atrai-1.0.jar interpret atrai.interpreters.LET.
LetInterpreter test.let
```

If you have implemented your interpreter, say atrai.interpreters.LETREC.
LetrecInterpreter, by extending atrai.interpreters.common.Interpreter,
then you can run the interpreter as follows:

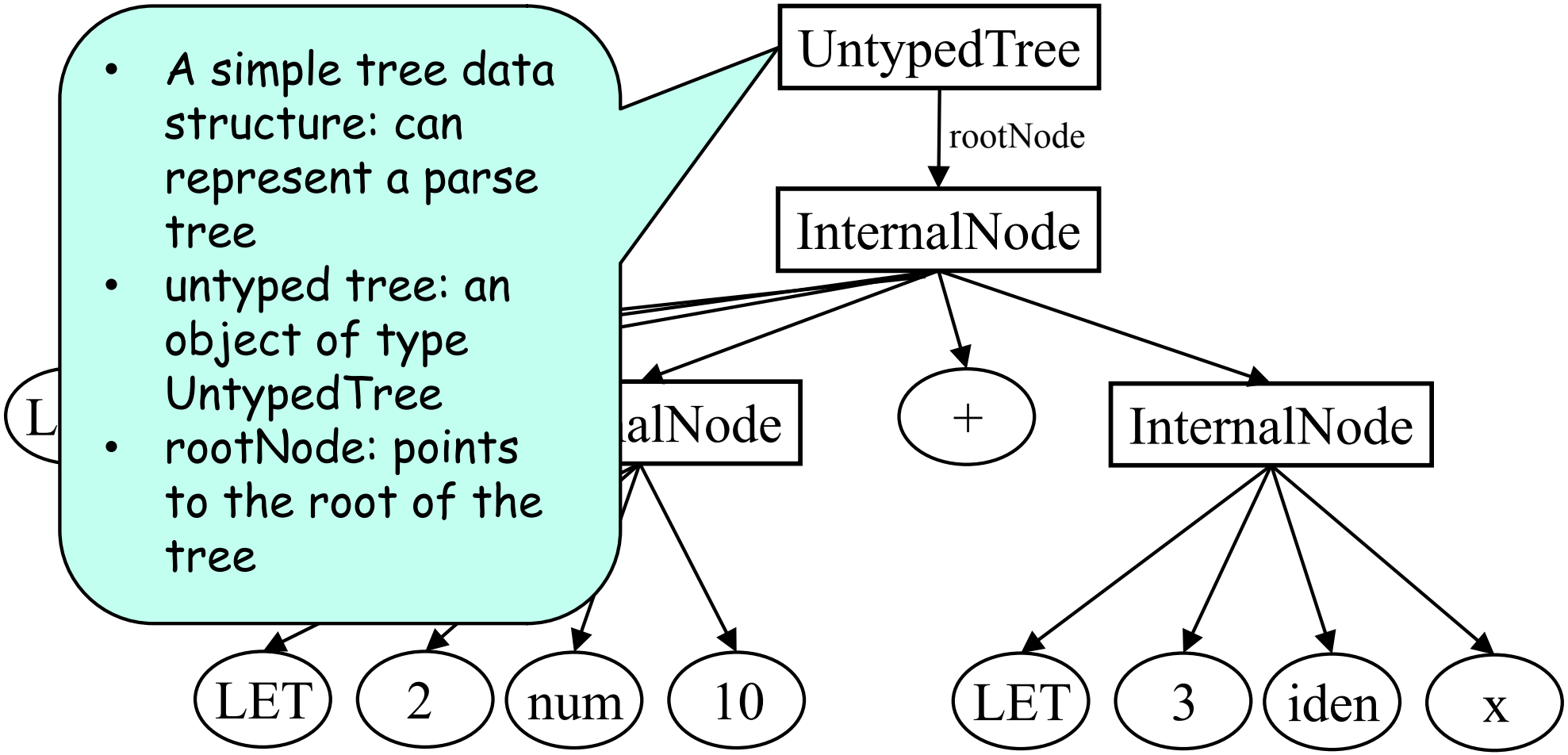
```
mvn clean package
java -jar lib/atrai-1.0.jar interpret atrai.interpreters.
LETREC.LetrecInterpreter test.letrec
```

Untyped Tree

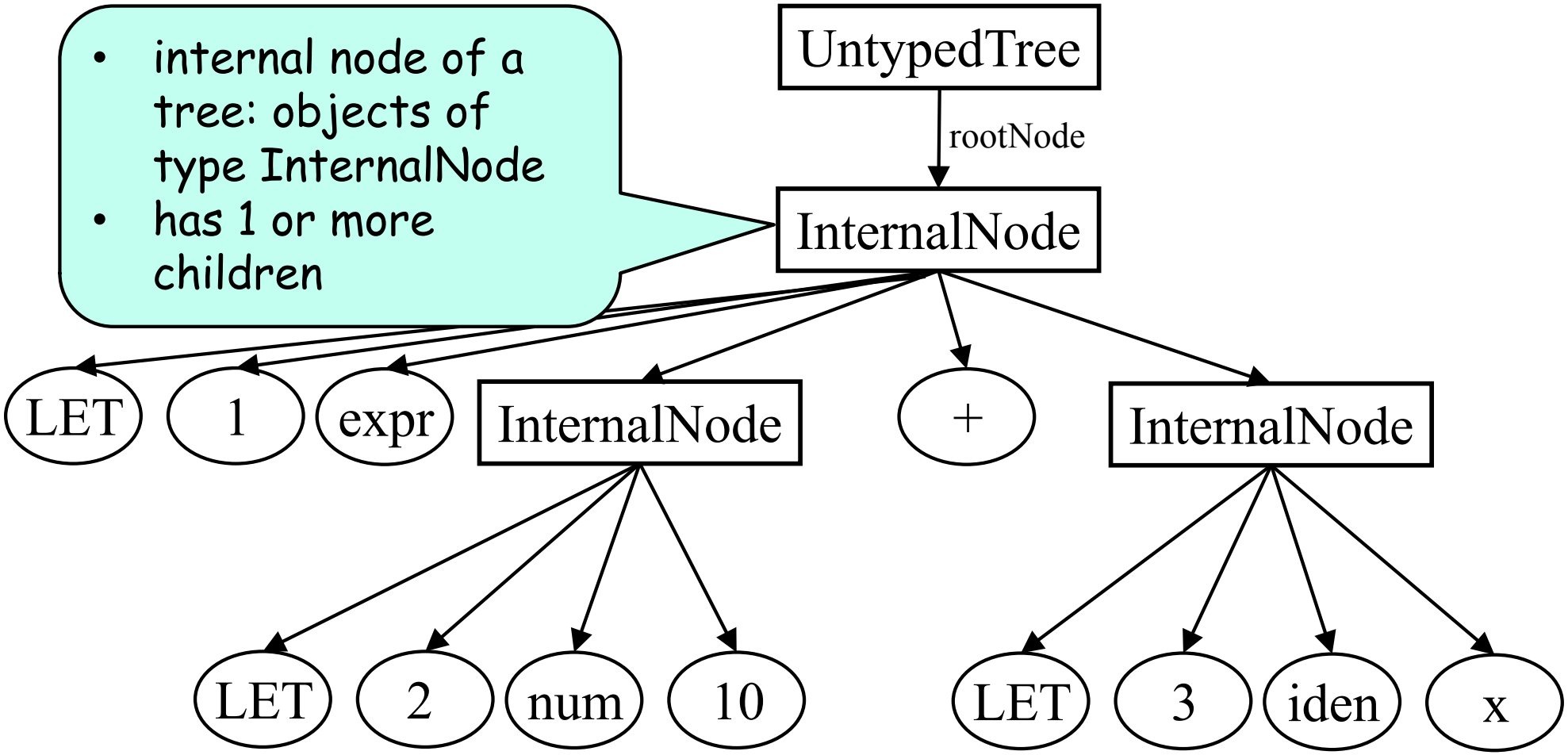


Untyped Tree

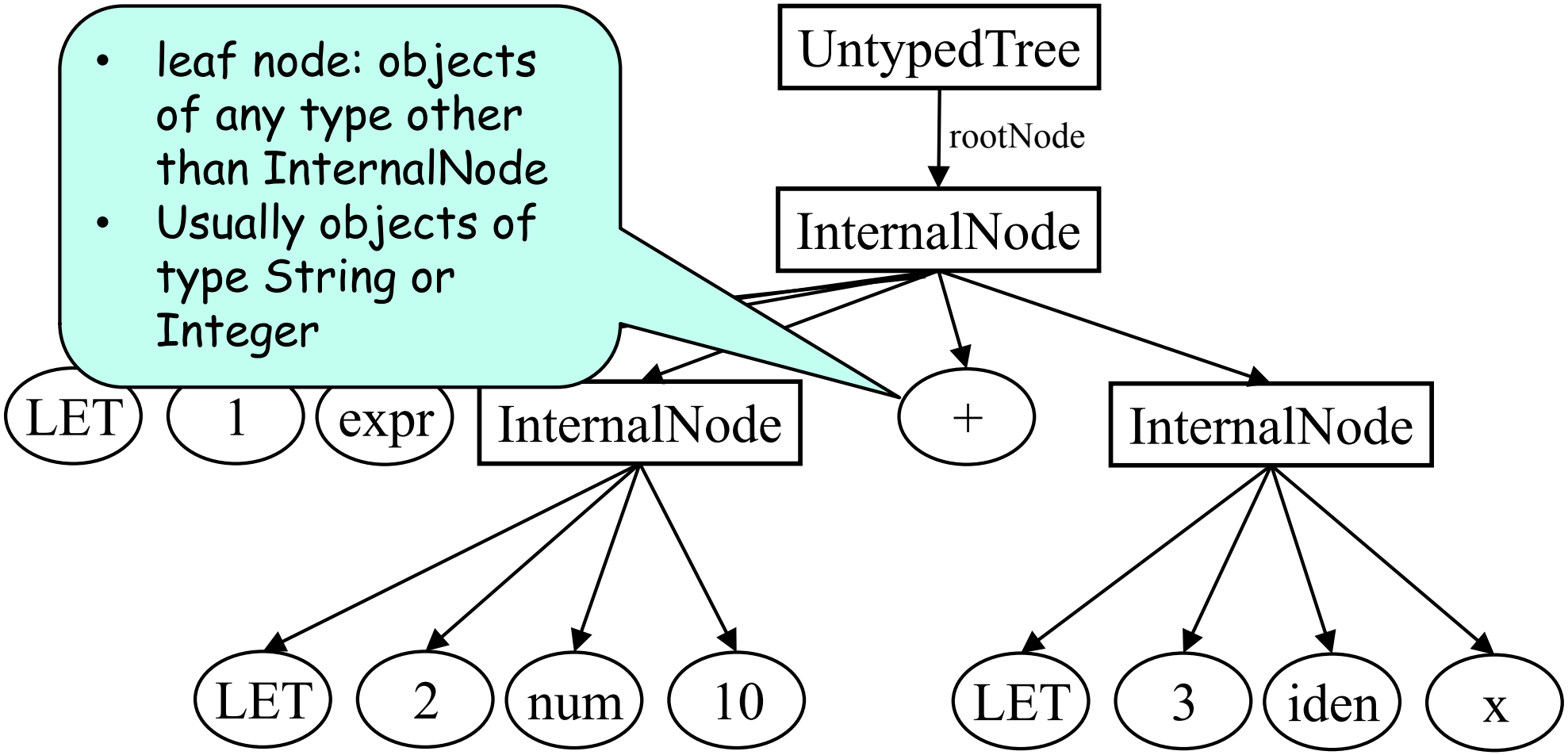
- A simple tree data structure: can represent a parse tree
- untyped tree: an object of type UntypedTree
- rootNode: points to the root of the tree



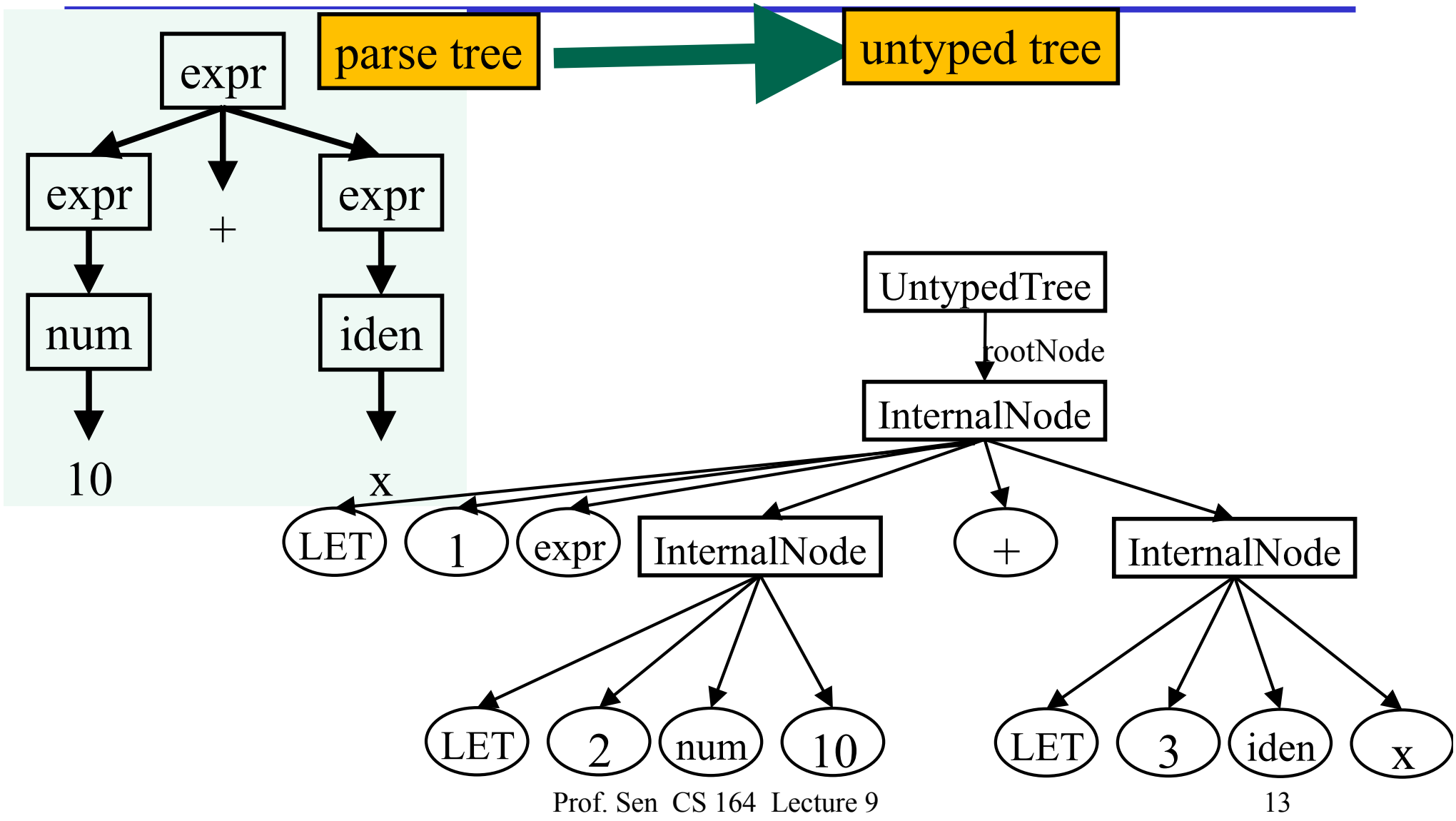
Untyped Tree



Untyped Tree



Untyped tree can represent a parse tree



General conventions in representing a parse tree using an untyped tree

- First child of any sub-untyped tree is the name of the language/grammar
- Second child after is an unique id
  - id maps to location in the original program string
- Third child is the name of the non-terminal which forms the root of the subtree
- We can deviate from this convention if necessary

Create Untyped Tree from a Parse Tree

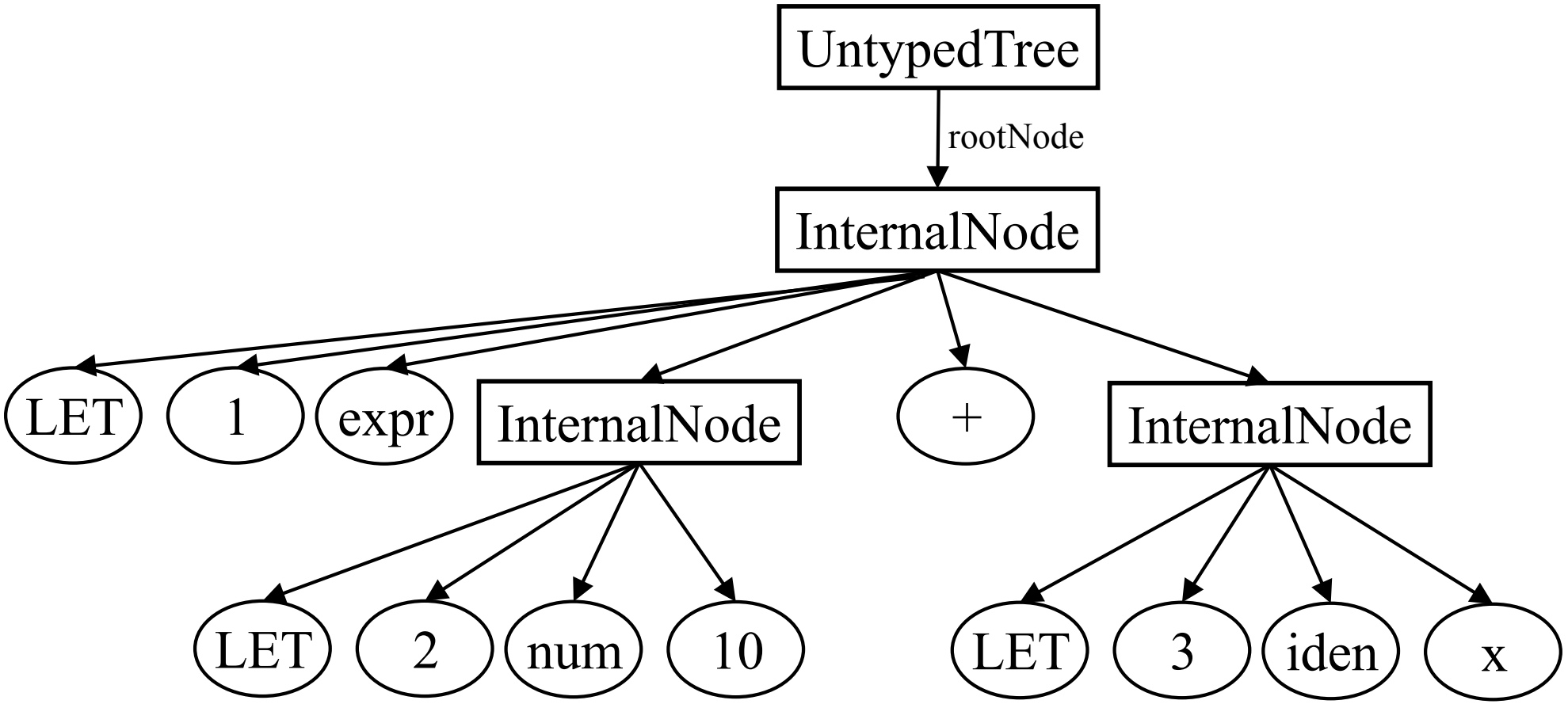
Pseudo-code:

```
counter = 1;
languageName = "LET";
createTree(tree) { // tree is a parse tree
        ret = new InternalNode();
        ret.addChild(languageName)
        ret.addChild(counter)
        ret.addChild(tree.name);
        counter++;
        for each child of tree
                if child is a tree
                        ret.addChild(createTree(child));
                else
                        ret.addChild(child);
        return ret;
}
createUntypedTree(tree) {
        UntypedTree ut = new UntypedTree();
        ut.setRoot(createTree(tree));
        return ut;
}
```

Untyped Tree

String representation of an untyped tree:

- (%LET 1 expr (%LET 2 num 10%) + (%LET 3 iden x%)%)



Facts about an untyped tree

- Textual representation of a tree
  - can be used for debugging
  - can express textual patterns over untyped trees
  - can express textual templates for creating untyped trees
- Similar to S-expressions in LISP
- Has balanced (%, and %) meta-characters
- Captures the syntactic structure of an untyped tree
- If we erase (%, %), and the first three leaves after each (%, we get the original program except the whitespaces
- Use ` to escape any character including `

Creating a Untyped Tree from an Untyped Tree

```
serialize(tree) { // tree is an untyped tree
        ret = "(%";
        for each child of tree
                if child is a tree
                        ret = ret + serialize(child);
                else
                        ret = ret + " " +child;
        ret = ret + "%)"
        return ret;
}
```

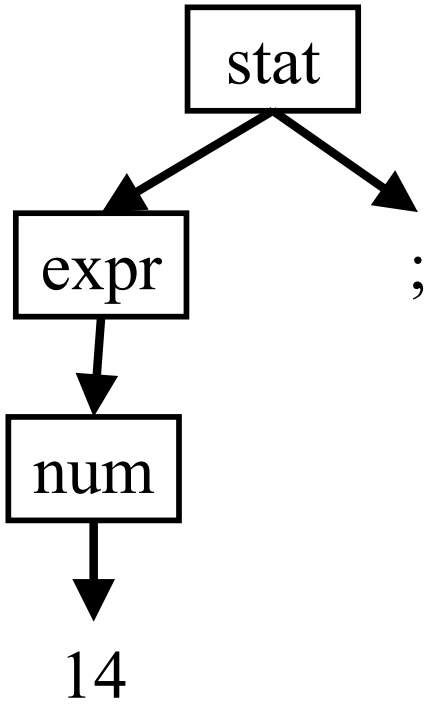
Example of an Untyped Tree and the Corresponding Parse Tree

Given grammar Ex:

Untyped tree of the program: 14 ;

is

```
(%Ex 1 stat
        (%Ex 2 expr (%Ex 3 num 14%)%)
        ;
%)
```



Example of an Untyped Tree and the Corresponding Parse Tree

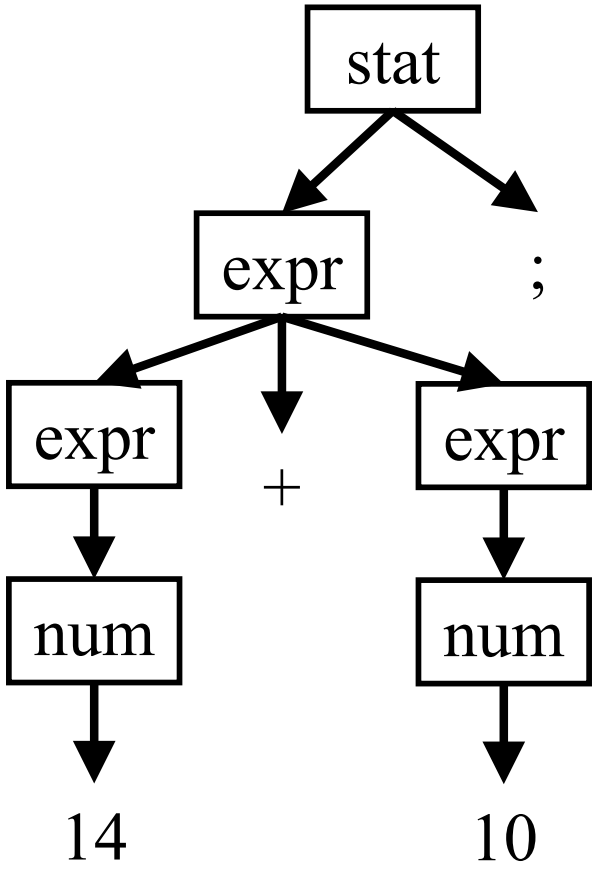
Given grammar Ex:

Serialized untyped tree of the program:

14 + 10 ;

is

```
(%Ex 1 stat
     (%Ex 2 expr
          (%Ex 3 expr (%Ex 4 num 14%)%)
          +
          (%Ex 5 expr (%Ex 6 num 10%)%)
     %)
     ;
%)
```



UntypedTree class

A untyped tree is an instance of the class UntypedTree and has a reference to the root node, which is either an internal node or a leaf.

```
class UntypedTree  extends Tree {
        static UntypedTree parse(String src, Lexer lexer);
        public Object getRoot();
        public Location getLocationFromID(int id);
        public String toString();
        public String toIndentedString();
}
```

Check javadocs/index.html for further documentation

See src/main/java/atra/core/UntypedTree.java for source

See src/test/java/atrai/core/TreeNodeTest.java for examples

InternalNode

An internal node in an untyped tree is an instance of the class InternalNode and has a non-zero number of children.

```
class InternalNode extends TreeNode {
        // iterates each child and applies lambda to the child
        Object iterate(Reducer lambda, Object initialReductionValue, Object context);
        String toString();
        String toIndentedString();
}
```

Check javadocs/index.html for further documentation
See src/main/java/atra/core/InternalNode.java for source

Generate Untyped Tree from an ANTLR 4 grammar

- One can use **GenericAntlrToUntypedTree** to generate an untyped tree from a string and a grammar

```
GenericAntlrToUntypedTree p = new GenericAntlrToUntypedTree();
UntypedTree st =
        p.parseStringToUntypedTree("Ex", "Ex", "stat", "1 + 2 * 3;");
System.out.println(st.toIndentedString());
// 1st argument is the name of the language
// 2nd argument is the name of the parser: often same as the 1st argument
// 3rd argument is the start symbol in the grammar
// 4th argument is the string to be parsed and converted to a Untyped Tree
p.parseFileToUntypedTree("Ex", "Ex", "stat", "myprogram.ex");
```

Leaves are always objects of type String except the unique ids which are Integers

Generate Untyped Tree from an ANTLR 4 grammar

- Example can be found in the methods parseFile and parseString in the file src/main/java/atrai/interpreters/LET/LetInterpreter.java

Convert a Serialized Untyped Tree to an Untyped Tree and vice-versa

```
// create a lexer which is used to tokenize strings in a Pattern
ANTLRTokenizer lexer = new ANTLRTokenizer("Ex");

// create an Untyped Tree from a Serialized Untyped Tree
UntypedTree st = UntypedTree.parse("(%Ex 2 expr (%Ex 3 num
14%)%)", lexer);

// create a Serialized Untyped Tree from an Untyped Tree
String s = st.toString();
// or
s = st.toIndentedString();
```

See src/test/java/atrai/core/TreeNodeTest.java for example transformations

Patterns

- A pattern is like a regular expression
  - is used to match an untyped tree
  - to capture parts of the matched untyped tree
- A pattern is again a untyped Tree
  - with special symbols @, @_, @*, @*_
  - @ matches any subtree or leaf
  - @_ matches any subtrees or leaves, and creates a capture group
  - @* matches 0 or more subtrees or leaves
  - @*_ matches 0 or more subtree or leaf and captures them as an array of objects
  - an internal node can have at most one of @* or @*_ as its direct child

Example of a Pattern

Given grammar Ex:
An example pattern is (%Ex @ num @_%)
The pattern matches the following Untyped Tree:

(%Ex 1 num 14%)

A successful match returns capture, which is an array of captures:
capture[0] = (%Ex 1 num 14%) //the entire matched untyped tree as an instance of UntypedTree
capture[1] = 14

Example of a Pattern

Given grammar Ex:
An example pattern is (%Ex @_ expr (%Ex @ num @_%)%)
The pattern matches the following Untyped Tree:

(%Ex 1 expr (%Ex 2 num 14%)%)

A successful match returns capture, which is an array of captures:
capture[0] = (%Ex 1 expr (%Ex 2 num 14%)%)
capture[1] = 1
capture[2] = 14

Example of a Pattern

Given grammar Ex:

An example pattern is (%@*_%) // captures all children as an array

The pattern matches the following Untyped Tree:

(%Ex 1 expr (%Ex 3 num 14%) + (%Ex 3 num 15%)%)

A successful match returns capture, which is an array of captures:

capture[0] = the entire untyped tree // as an instance of UntypedTree

capture[1] = [Ex, 1, expr, (%Ex 3 num 14%), +, (%Ex 3 num 15%)]

Example of a Pattern

Given grammar Ex:

An example pattern is (%Ex @_ expr @*_%)

The pattern matches the following Untyped Tree:

```
(%Ex 1 expr
        (%Ex 2 expr (%Ex 3 num 14%)%)
        +
        (%Ex 4 expr (%Ex 5 num 10%)%)
%)
```

A successful match returns capture, which is an array of captures:

capture[0] = the entire untyped tree // as an instance of UntypedTree

capture[1] = 1

capture[2] = [(%Ex 2 expr (%Ex 3 num 14%)%), +, (%Ex 4 expr (%Ex 5 num 10%)%)] // an array of objects

Example of a Pattern

Given grammar Ex:

An example pattern is (%Ex @_ expr @*%)

The pattern matches the following Untyped Tree:

```
(%Ex 1 expr
        (%Ex 2 expr (%Ex 3 num 14%)%)
        +
        (%Ex 4 expr (%Ex 5 num 10%)%)
%)
```

A successful match returns capture, which is an array of captures:

capture[0] = the entire untyped tree // as an instance of UntypedTree

capture[1] = 1

Pattern API

```
class Pattern extends Tree {
        // create a pattern from a string and a lexer
        static Pattern parse(String pattern, Lexer lexer);
        // matches the pattern against an untyped tree
        // returns the array of captures or null (if match fails)
        Object[] match(UntypedTree tree);
        // matches the pattern against a node or a leaf
        // returns the array of captures or null (if match fails)
        Object[] match(Object node);
        // returns the array of captures from the last match
        Object[] getMatches();
        // returns the object at index from the last capture array
        Object getMatch(int index);
}
```

Check javadocs/index.html for further documentation

See src/main/java/atra/core/Pattern.java for source

See src/test/java/atrai/core/PatternTest.java for examples

Example of a Pattern in Atrai

```
// create a lexer which is used to tokenize strings in a Pattern
ANTLRTokenizer lexer = new ANTLRTokenizer("Ex");
// create a pattern from a string in serailized untyped tree form
Pattern p = Pattern.parse("(%Ex @ num @_%)", lexer);
// match the pattern against an untyped tree st
Object[] captures =  p.match(st);
// returns null if match fails
```

Example Usage of the Pattern API

```
String pattern = "(% if (@_) (%{ @_ }%) else @_ %)";
String source = "(%if ( (% x > 0%) ) (% { (%x = (%- x%) %) }%) else (% (% x %) = (%x
+ 1%)%)%)";
Lexer lexer = new SimpleStringTokenizer();
UntypedTree s = UntypedTree.parse(source, lexer);
Pattern p = Pattern.parse(pattern, lexer);
Object[] captures =  p.match(s);

// captures[0] is the untyped tree corresponding to source
// captures[1] = (%x > 0%)
// captures[2] = (%x = (%- x%)%)
// captures[3] = (%(%x%) = (%x + 1%)%)
```

SimpleStringTokenizer is a simple Lexer that uses Java's StringTokenizer to tokenize a string.
See src/test/java/atrai/core/PatternTest.java for more examples

Transformer: for matching and modifying an untyped tree, node, or leaf

- A set of pattern/action pairs: (p, a)
  - where p is a pattern given as a string
  - a is a lambda that takes an array of captures and a context and returns an object
- If an untyped tree or a node matches pattern p and returns the array of captures c
  - then call a(c) and return the result
- Example:

```
(%Ex @ num @_%), (captures, E) -> {return captures[1]; }
(%Ex @ expr @_ + @_ %), (captures, E) -> { return captures[1] + captures[2];}
```

Transformer API

```
Transformer.addTransformer(PatternTree pattern, BiFunction<Object[],
Object, Object> action);
Transformer transformer = new Transformer(lexer);
transformer.addTransformer("(%Ex @ num @_%)", (captures, E) -> {
                                                return captures[1]; });
transformer.addTransformer("(%Ex @ expr @_ + @_ %)", (captures,E) -> {
                                    return captures[1] + captures[2];}
st = transformer.transform(st, E);  // E is some arbitrary object used to
                                                // pass information to actions
```

- Let [(p1, a1), (p2, a2), ..., (pn, an)] be the set of pattern/action pairs in a transformer
- if p1 matches st and returns captures c, then set st to a1(c, E)
- if p2 matches st and returns captures c, then set st to a2(c, E)
- ...
- if pn matches st and returns captures c, then set st to an(c, E)

Note: one can call transformer.transform on a subtree inside an action

Sample Transformer for LET

See src/main/java/ atrai/interpreters/LET/LetInterpreter.java

```
ANTLRTokenizer tokenizer = new ANTLRTokenizer(grammarName);

Transformer transformer = new Transformer(tokenizer);

transformer.addTransformer("(%LET @_ expr @_ + @_%)", (c, E) -> {
   Location l = st.getLocationFromID((Integer) c[1]);
   return i(transformer.transform(c[2], E), l) + i(transformer.transform(c[3], E), l);
});

transformer.addTransformer("(%LET @_ expr ( @_ )%)", (c, E) -> {
   Location l = st.getLocationFromID((Integer) c[1]);
   return transformer.transform(c[2], E);
});

transformer.addTransformer("(%LET @_ num @_%)", (c, E) -> {
   Location l = st.getLocationFromID((Integer) c[1]);
   return s2i(c[2], l);
});
```

Sample Transformer for LET

```
transformer.addTransformer("(%LET @_ iden @_%)", (c, E) -> {
   Location l = st.getLocationFromID((Integer) c[1]);
   return e(E).get(s(transformer.transform(c[2], E), l));
});

transformer.addTransformer("(%LET @_ expr let (%LET @_ iden @_%) = @_ in @_%)", (c, E) -> {
   Location l = st.getLocationFromID((Integer) c[1]);
   Environment Ep = Environment.extend(s(c[3], l), i(transformer.transform(c[4], E), l), e(E));
   return transformer.transform(c[5], Ep);
});

transformer.addTransformer("(%LET @_ expr if @_ then @_ else @_%)", (c, E) -> {
   Location l = st.getLocationFromID((Integer) c[1]);
   if (b(transformer.transform(c[2], E), l)) {
      return transformer.transform(c[3], E);
   } else {
      return transformer.transform(c[4], E);
   }
});
```

DynamicTypeChecker.java

- See src/main/java/ atrai/interpreters/common/DynamicTypeChecker.java to see a dynamic type casting methods which we used in the LET interpreter.

```
// Casts o to int and returns the int.  Throws exception if casting fails.
public static int i(Object o, Location location) {
   if (o instanceof Integer) {
      return (Integer) o;
   } else {
      throw new SemanticException("Dynamic type checking failed: expecting int instead of " +
o, location);
   }
}
// Casts o to Environment and return the Environment object.  Throws exception if casting fails.
public static Environment e(Object o) {
   if (o == null) return null;
   if (o instanceof Environment) {
      return (Environment) o;
   } else {
      throw new RuntimeException("Internal error: expecting object of type Environment instead
of " + o);
   }
}
```

Debugging Transformer.transform

- If a transformer is not working as expected, we want to debug its behavior on a tree
- pass -Ddebug1=true to java, to print the (p,a) pairs that were successfully applied
- pass -Ddebug2=true to java, to print the (p,a) pairs that were not successfully applied

Template

- Like a template string in regular expressions
  - remember s/pattern/template/ in regex
  - used in conjunction with a pattern
  - a template of an untyped tree that replaces the matched untyped tree
  - use to transform an untyped tree to another
- A template is again an untyped tree
  - with special tokens of the form $n, $$n, $*
  - $n is replaced with the n^{th} capture
  - $$n is replaced with the children of the n^{th} capture
  - $*n is replaced with the elements of the n^{th} capture
    - the n^{th} capture must be an array (possibly captured using @*_)

Example of a Pattern/Template pair

Given grammar Ex:
An example pattern is (%Ex @_ expr @_ + @_%)
An example template is (%Ex $1 expr $3 + $2%)
The pattern matches the following Untyped Tree:

```
(%Ex 1 expr
        (%Ex 2 expr (%Ex 3 id x%)%)
        +
        (%Ex 4 expr (%Ex 5 num 10%)%)
%)
```

The transformed tree is

```
(%Ex 1 expr
        (%Ex 4 expr (%Ex 5 num 10%)%)
        +
        (%Ex 2 expr (%Ex 3 id x%)%)
%)
```

Example of a Pattern/Template pair

Given grammar Ex:

An example pattern is (%Ex @_ expr (%Ex @ num @_%)%)

An example template is (%Ex $1 num $2%)

The pattern matches the following Untyped Tree:

(%Ex 2 expr (%Ex 3 num 10%)%)

The transformed tree is

(%Ex 2 num 10%)

Example of a Pattern/Template pair

Given grammar Ex:

An example pattern is (%Ex @_ expr @_%)

An example template is (%Ex $1 num $$2%)

The pattern matches the following Untyped Tree:

(%Ex 2 expr (%Ex 3 num 10%)%)

The transformed tree is

(%Ex 2 num Ex 3 num 10%)

Example of a Pattern/Template pair

An example pattern is (%@_ @*_%)

An example template is (%$*2 $1%)

The pattern matches the following Untyped Tree:

(%(%1 2%) 3 4 5 6 7%)

The transformed tree is

(%3 4 5 6 7 (%1 2%)%)

Template API

```
class Template extends Tree {
        // create a template from a string and a lexer
        static Template parse(String template, Lexer lexer);
        // construct a tree by replacing $n with nth capture in captures
        // return the resulting tree
        Object replace(Object[] captures);
}
```

Check javadocs/index.html for further documentation
See src/main/java/atra/core/Template.java for source
See src/test/java/atrai/core/TemplateTest.java for examples

Pattern/Template in Atrai

```
// create a lexer used to tokenize strings in a Pattern
ANTLRTokenizer lexer = new ANTLRTokenizer("Ex");
// create a pattern
Pattern p = Pattern.parse("(% @_ expr (%Ex @ num @_%)%)", lexer);
// match the pattern against a Untyped tree st
// returns null if match fails
Object[] captures =  p.match(st);

// create a template
Template r = Template.parse("(% $1 num $2%)", lexer);
// create the transformed tree
st = r.replace(st);
```

An Example Usage of Pattern/Template API

```
public void test3() throws Exception {
    String pattern = "(% @_ @_ %)";
    String source = "(%hello (%world X%)%)";
    String template = "(% begin `$1 $2 `$3_ end %)";
    Lexer lexer = new SimpleStringTokenizer();
    UntypedTree s = UntypedTree.parse(source, lexer);
    Pattern p = Pattern.parse(pattern, lexer);
    Template t = Template.parse(template, lexer);
    Object t = t.replace(p.match(s));
    System.out.println(t);
    assertEquals("(%begin `$1 (%world X%) `$3_ end%)", t.toString());
}
```

`$1 is not considered as hole because ` escapes $.

See src/test/java/atrai/core/TemplateTest.java for more examples

Usage of $$n in Template

```
public void test1() throws Exception {
    String pattern = "@_";
    String source = "(%hello world%)";
    String template = "(% begin $$1 end %)";
    Lexer lexer = new SimpleStringTokenizer();
    UntypedTree s = UntypedTree.parse(source, lexer);
    Pattern p = Pattern.parse(pattern, lexer);
    Template t = Template.parse(template, lexer);
    Object t = t.replace(p.match(s));
    assertEquals("(%begin hello world end%)", t.toString());
}
```

p.match(s) returns captures where captures[0] = captures[1] = **(%hello world%)**

$$1 gets replaced by the children of (%hello world%)

Usage of $*n in Template

```
public void test1() throws Exception {
    String pattern = "(% @_ (%world @*%) %)";
    String source = "(%hello (%world X Y Z%)%)";
    String template = "(% begin $1 $*2 end %)";
    Lexer lexer = new SimpleStringTokenizer();
    UntypedTree s = UntypedTree.parse(source, lexer);
    Pattern p = Pattern.parse(pattern, lexer);
    Template t = Template.parse(template, lexer);
    Object t = t.replace(p.match(s));
    assertEquals("(%begin hello X Y Z end%)", t.toString());
}
```

p.match(s) returns captures where captures[2] = **[X, Y, Z]**

$*2 gets replaced by the elements of [X, Y, Z]

Transformer API with Templates and Modifiers

Transformer.addTransformer(PatternTree pattern, BiConsumer<Object[], Object> modifier, Template template);

```
Transformer transformer = new Transformer(lexer);
transformer.addTransformer("(%Ex @_ expr @_ + @_ %)", (captures,E) -> {
            captures[2] = captures[2] + captures[3];}, "(%Ex $1 num $2%)");
transformer.addTransformer("(%Ex @_ num @_%)", (captures, E) -> {
            captures[2] = Integer.parseInt(captures[2]; }, "$2" );
st = transformer.transform(st, E);  // E is some arbitrary object used to
                                                    // pass information to actions
```

- Let [(p1, a1, t1), (p2, a2, t2), ..., (pn, an, tn)] be the set of pattern/action/template triplets in a transformer
- if p1 matches st and returns captures c, then apply a1(c,E) and set st to t1.replace(c)
- if p2 matches st and returns captures c, then apply a2(c,E) and set st to t2.replace(c)
- ...
- if pn matches st and returns captures c, then apply an(c,E) and set st to tn.replace(c)

Note: one can call transformer.transform on a subtree inside an action

Transformer API with Templates and Pure Modifiers

Transformer.addTransformer(PatternTree pattern, BiFunction<Object[], Object, Object[]> pureModifier, Template template);

- Let [(p1, a1, t1), (p2, a2, t2), ..., (pn, an, tn)] be the set of pattern/action/template triplets in a transformer
- if p1 matches st and returns captures c, then if a1(c, E) is not null, set st to to t1.replace(a1(c, E))
- if p2 matches st and returns captures c, then if a2(c, E) is not null, set st to to t2.replace(a2(c, E))
- ...
- if pn matches st and returns captures c, then if an(c, E) is not null, set st to to tn.replace(an(c, E))

Note: an action can return null to keep st unchanged

Note: one can mix and match calls to all forms of addTranformer in a single transformer

Note: the pairs and triplets in a transformer are applied in the order in which they were added