L11: Metalinguistic Abstraction

CS1101S: Programming Methodology

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October 26, 2022

Module Overview

- Unit 1—Functions (textbook Chapter 1)
  - Getting acquainted with programming, using functional abstraction
  - Learning to read programs, statically, and using the substitution model
  - Example applications: Runes, curves
- Unit 2—Data (textbook Chapter 2)
  - Getting familiar with data: pairs, lists, trees
  - Searching in lists and trees, sorting of lists
  - Example application: sound processing

Module Overview, continued

- Unit 3—State (parts of textbook Chapter 3)
  - Programming with stateful abstractions
  - Arrays, loops, searching in and sorting of arrays
  - Reading programs using the **environment model**
  - Example applications: robots, video processing
- Unit 4—Beyond (parts of textbook Chapters 3 and 4)
  - Streams (example application: video stream processing)
  - **Metalinguistic abstraction: understanding environment model by programming it**

CP3108: A project module on "Source Academy"

Time and workload: Sem 2 AY2022/23; CP3108A/B (2/4 MC)

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Interviews: 14/11–2/12/2022

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Time and workload: Sem 2 AY2022/23; CP3108A/B (2/4 MC)

Application: from Friday Week 11 to Friday Week 13

Interviews: 14/11–2/12/2022

Scope: topics listed in application form; look out for announcements

Avenger recruitment

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Interviews: throughout Sem 2

Selection: first round before end of Sem 2; waiting list

Why a metacircular evaluator?

Recall: programming is...

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...communicating computational processes

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The model describes a computational process (frames etc) that unfolds *whenever any* program runs.

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...communicating computational processes

By now...

...we are quite effective in using Source for communicating computational processes

Consider the environment model...

The model describes a computational process (frames etc) that unfolds *whenever any* program runs.

Our goal today

Can we use Source to better understand the environment model?

Importance of metalinguistic abstraction

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The most fundamental idea in programming

The evaluator, which determines the meaning of statements and expressions in a programming language, is just another program.

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The evaluator, which determines the meaning of statements and expressions in a programming language, is just another program.

- Symbolic evaluator/differentiator in Lecture L6 is just another program!
- Source Academy where your programs run is just another program!
- Firmware that you uploaded to the EV3 LEGO Mindstorms computers is just another program!
- Environment visualizer is just another program!

The most beautiful program ever written

Gerald Jay Sussman, CS1101S Guest Lecture 2020/21, 25:35

"The most beautiful program ever written, in my opinion, is the Eval/Apply Interpreter."

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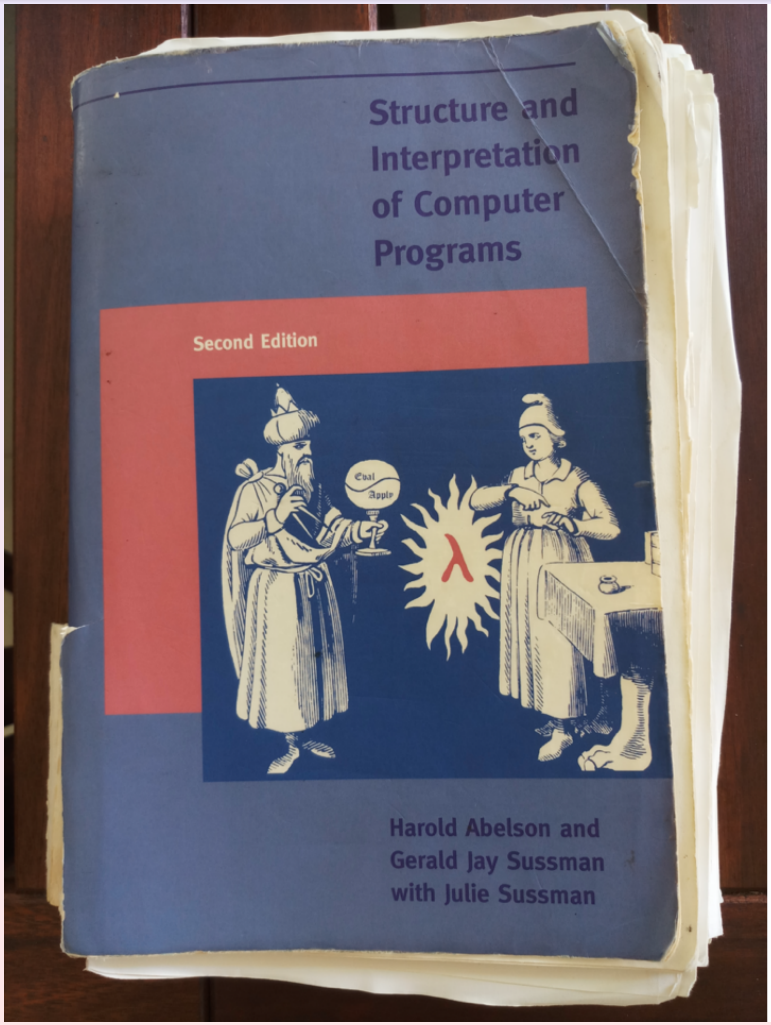
"The most beautiful program ever written, in my opinion, is the Eval/Apply Interpreter."

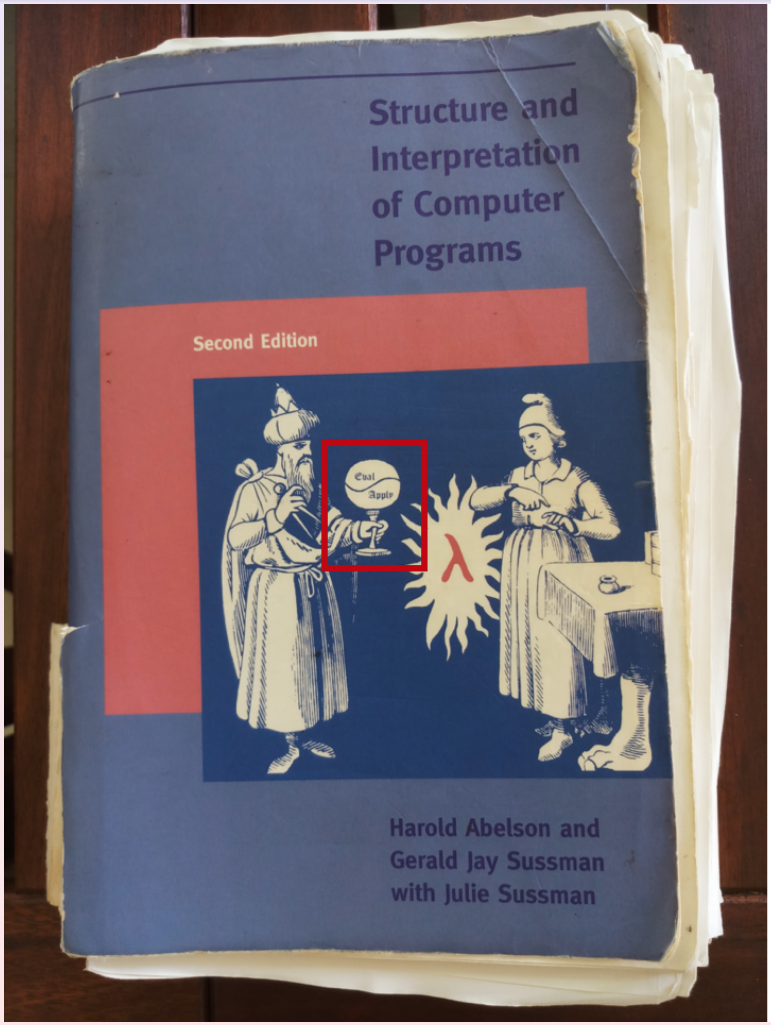
Why is this beautiful?

It is beautiful in the same way as Maxwell's Equations on electromagnetism are beautiful: It conveys deep insights in a few lines.

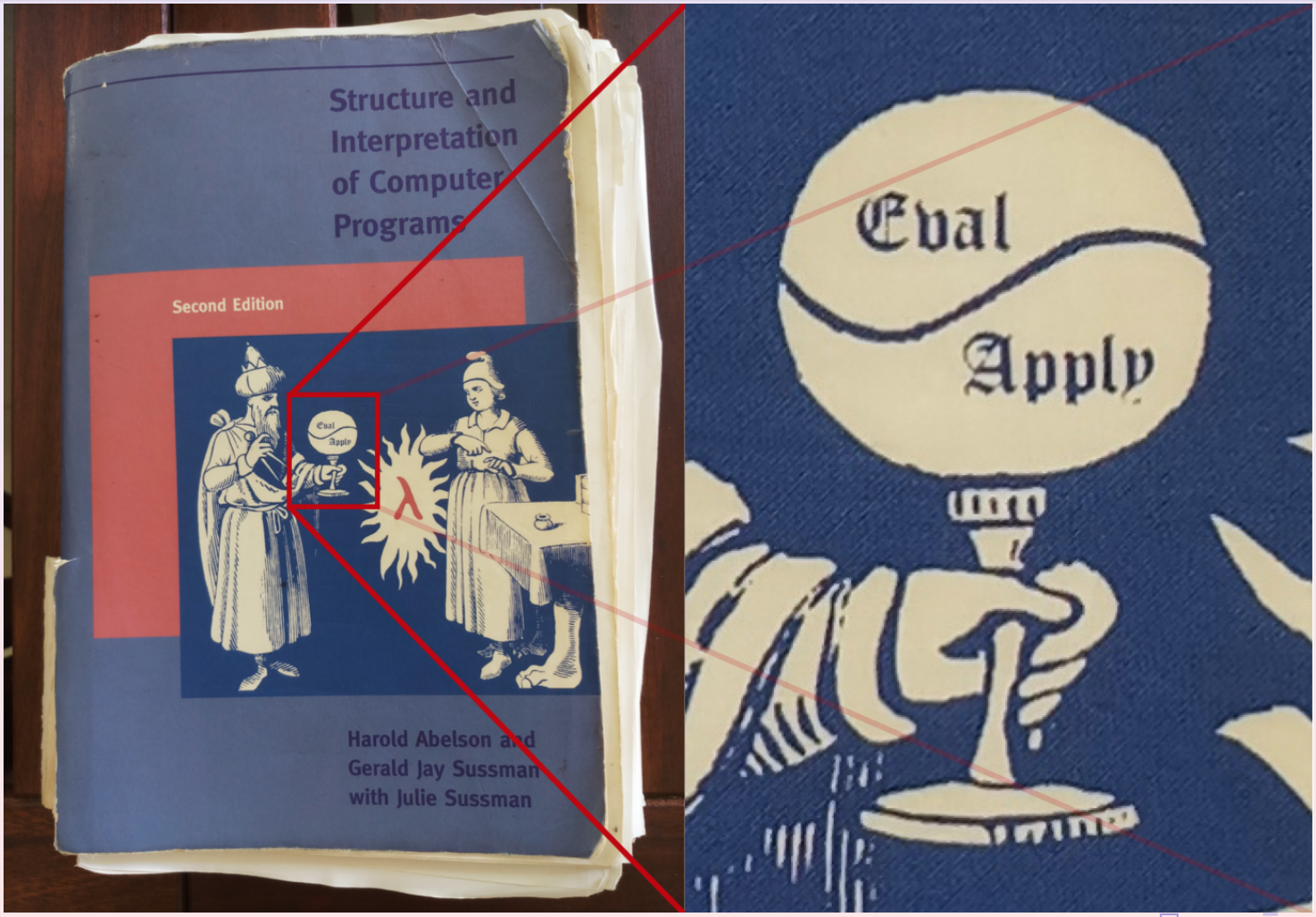
SICP


Structure and Interpretation of Computer Programs
Second Edition
Harold Abelson and
Gerald Jay Sussman
with Julie Sussman

SICP: What is that in the middle?

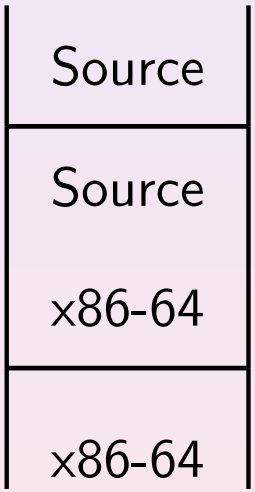


SICP: The importance of Eval/Apply

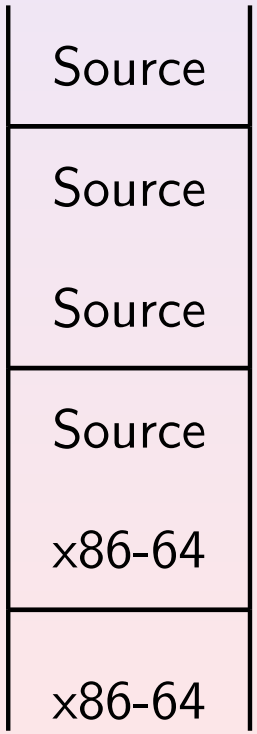


MetaCircular evaluator (MCE) as a language processor

`factorial` in Source Academy



`factorial` in MCE



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Objective

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Task

We want to write an evaluator in Source that can execute programs that are written in Source

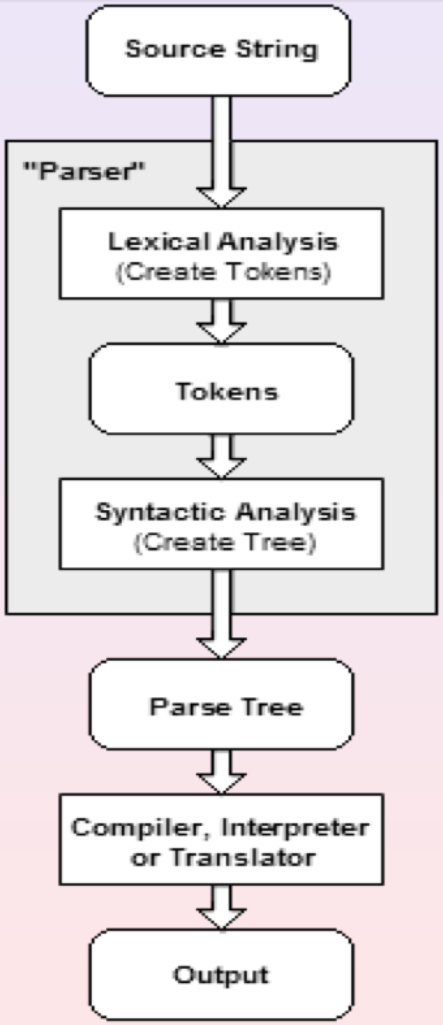
Why?

There is no *practical* use for such a *metacircular evaluator*. After all, in order to run the evaluator, you need to have already a working implementation of Source!

Objective

By writing a metacircular evaluator for Source, we hope to gain new insights into the language and a deeper understanding of the environment model.

First step for evaluator: parsing



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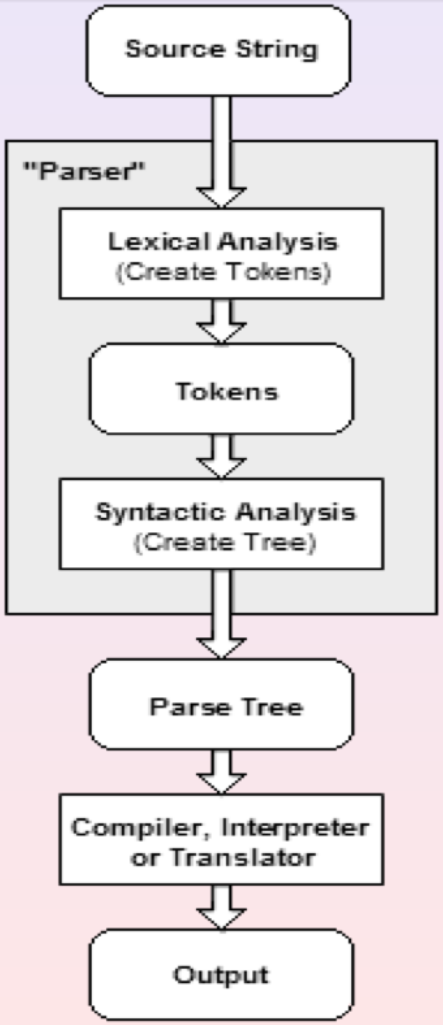
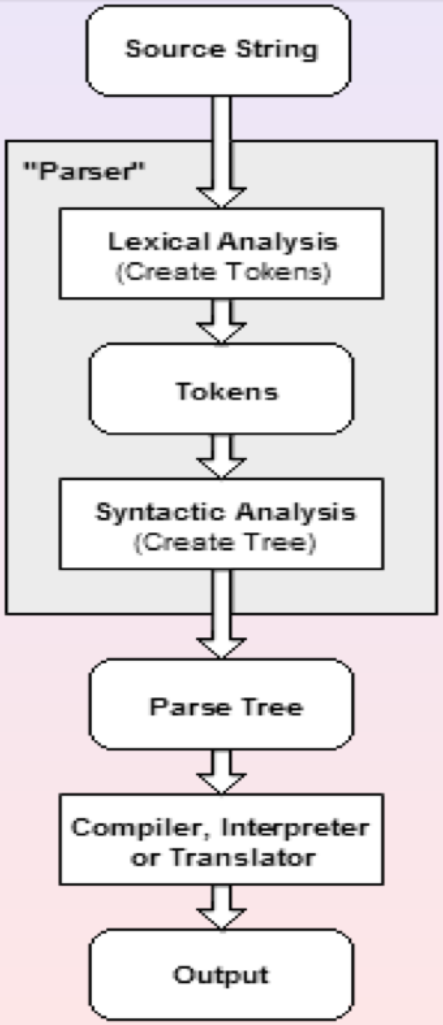


- Lexical analysis

First step for evaluator: parsing



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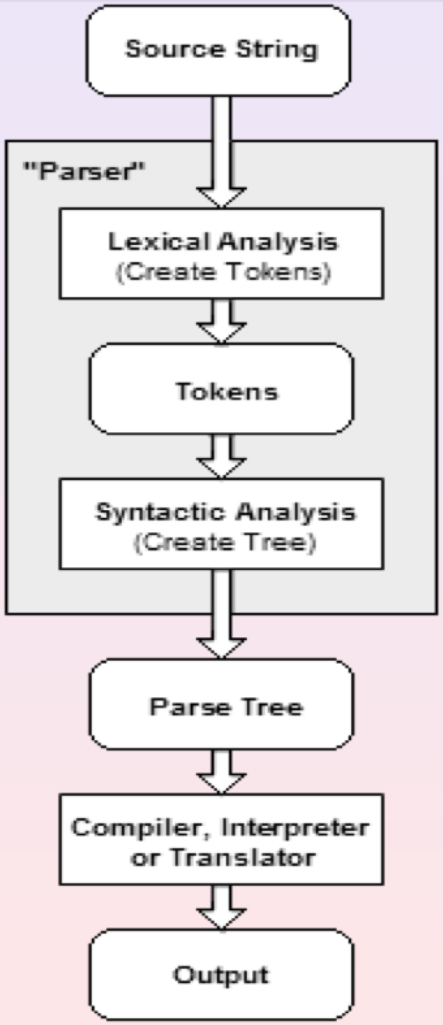

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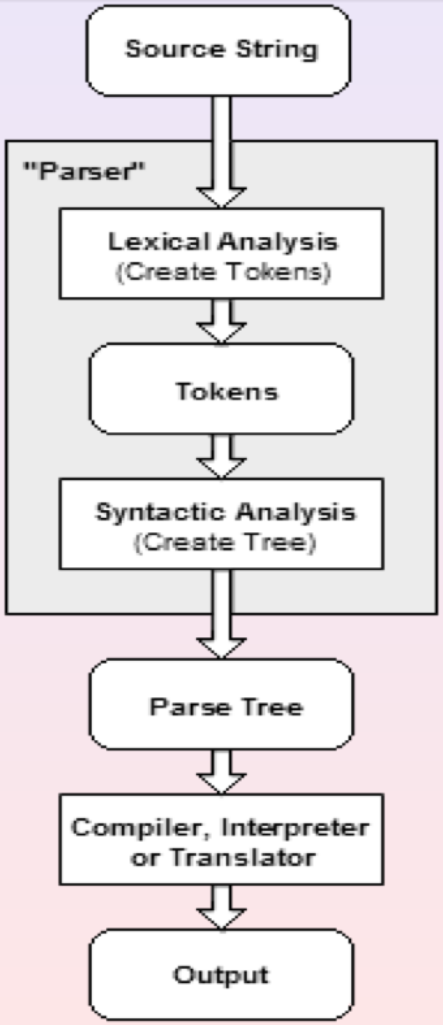

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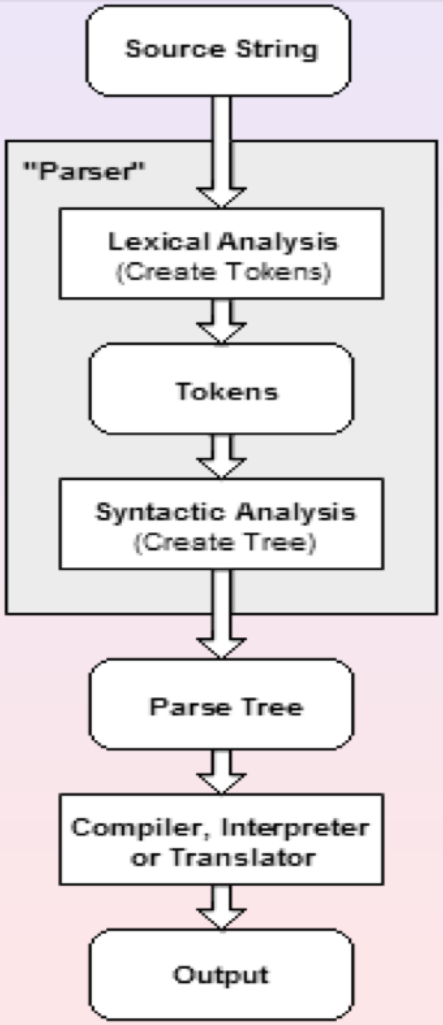

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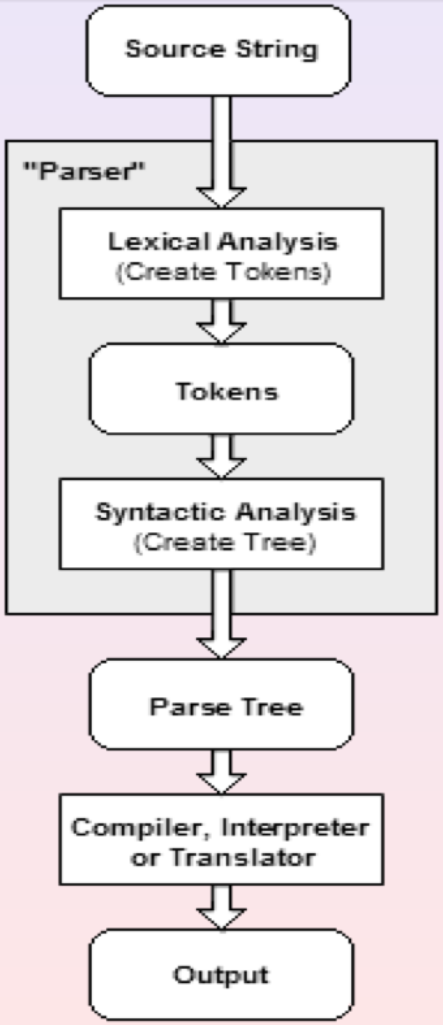

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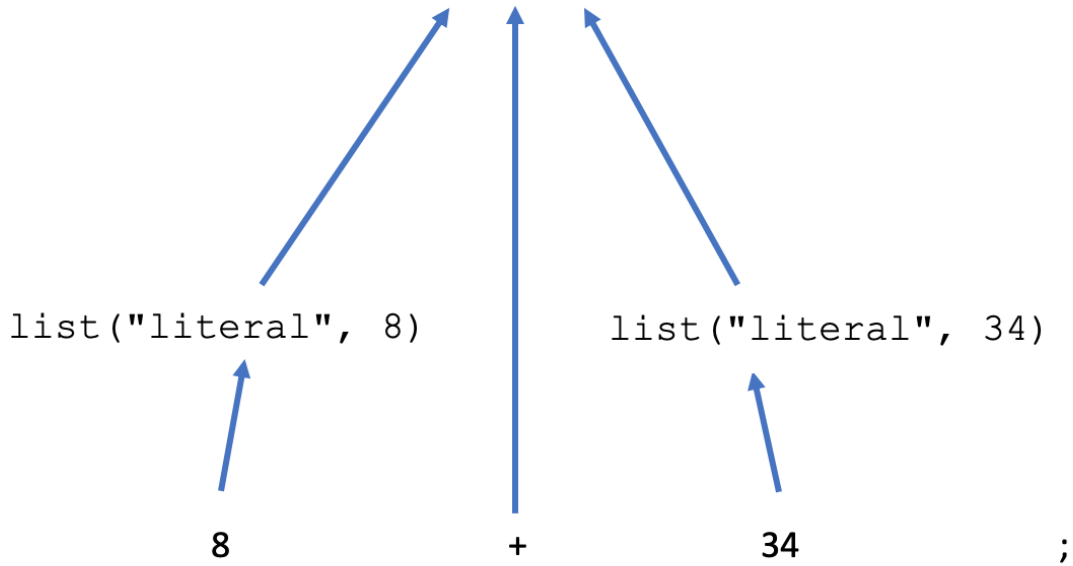
  - Example: `"8 + 34;"` is split into tokens `8` `+` `34` `;`
- Parsing
  - Checks that the tokens form allowable components
  - Produces symbolic representation of the program, a *syntax tree*

Syntax tree in graphical notation

```
list(
 "binary_operator_combination","+", list("literal", 8), list("literal", 34))
```



Support for parsing in Source §4

```
const syntax_tree
    = parse("8 + 34;");
```

generates the syntax tree as Source list:

```
display_list(syntax_tree);
```

displays

```
list("binary_operator_combination", "+",
     list("literal", 8), list("literal", 34))
```

Scope of L11 (also for Mission, PA, Final)

L11: evaluator for Source §1 without `return`

Sequence of evaluators describing the structure and interpretation of a simplified Source §1, starting with a "Calculator language"

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Reading

- SICP JS 4.1: L11

Calculator language in Backus-Naur Form (BNF)

stmt	::=	*expr* ;	expression statement
expr	::=	*expr bin-op expr*	binary operator combination
	|	*number*	number expression
	|	(*expr*)	parenthesised expression
bin-op	::=	+ | - | * | /	binary operator

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bin-op	::=	+ | - | * | /	binary operator

Example:

```
1.4 + 2.3 / 70.4;
```

Parsing the calculator language

To run the program

```
1.4 + 2.3 / 70.4;
```

we first parse it:

```
parse("1.4 + 2.3 / 70.4;");
```

returns the syntax tree

```
list("binary_operator_combination",
     "+",
     list("literal", 1.4),
     list("binary_operator_combination", "/",
          list("literal", 2.3),
          list("literal", 70.4)))
```

Syntax of literals

Example: parse("...38..."); ⇒
...list("literal", 38)...

```
// syntax predicate (in the following in maroon)
function is_literal(comp) {
  return is_tagged_list(comp, "literal");
}
function is_tagged_list(comp, the_tag) {
  return is_pair(comp) && head(comp) === the_tag;
}
// selector (in the following in blue)
function literal_value(comp) {
  return head(tail(comp));
}
```

Syntax of operator combinations

```
parse("... 2.3 + 70.4 ...");
```
$\Rightarrow$
```
... list("binary_operator_combination", "+",
         list("literal", 2.3),
         list("literal", 70.4)) ...
```

Syntax of operator combinations

```
parse("... 2.3 + 70.4 ...");⇒

... list("binary_operator_combination", "+",
         list("literal", 2.3),
         list("literal", 70.4)) ...

// syntax predicate (parsing details in 4.1.2)
const is_operator_combination = comp =>
is_tagged_list(comp,"binary_operator_combination"
// selectors
const op_comb_symbol      = comp => list_ref(comp,1);
const op_first_operand    = comp => list_ref(comp,2);
const op_second_operand = comp => list_ref(comp,3);
```

Evaluating the calculator language

```
function evaluate(expr) {
  return is_literal(expr)
    ? literal_value(expr)
    : is_operator_combination(expr)
    ? apply(op_comb_operator_symbol(expr),
        list_of_values(
          list(op_comb_first_operand(expr),
               op_comb_second_operand(expr))))
    : error(expr, "Unknown expression:");
}
```

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    : error(expr, "Unknown expression:");
}

function list_of_values(exprs) {
  return map(evaluate, exprs);
}
```

Applying operator combinations

Example: `2.3 / 70.4`

```
function apply(operator, operands)
{
    const first_op = head(operands);
    const second_op = head(tail(operands));
    return operator === "+"
           ? first_op + second_op
           : operator === "-"
           ? first_op - second_op
           : operator === "*"
           ? first_op * second_op
           : operator === "/"
           ? first_op / second_op : error(); }
```

Adding booleans, conditionals, and sequences

stmt	::=	$\cdots$	
	$\mid$	*stmt*$_1$ ... *stmt*$_n$	statement sequence
expr	::=	$\cdots$	
	$\mid$	`true` $\mid$ `false`	boolean literals
	$\mid$	*expr*$_1$? *expr*$_2$: *expr*$_3$	conditional expression

Example:

```
8 + 34; true ? 1 + 2 : 17;
```

Evaluating the language

```
function evaluate(comp) {
  return ... // handling literals, operator comb
    : is_conditional(comp)
    ? eval_conditional(comp)
    : is_sequence(comp)
    ? eval_sequence(sequence_statements(comp))
    : error(comp, "Unknown component:");
}
```

Parsing conditionals: an example

```
parse("true ? 42 : 17;");
```

returns

```
list("conditional_expression",
     list("literal", true),
     list("literal", 42),
     list("literal", 17))
```

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```
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returns

```
list("conditional_expression",
     list("literal", true),
     list("literal", 42),
     list("literal", 17))
```

Syntax predicate: `is_conditional`
Selectors: `cond_expr_pred`, `cond_expr_cons`, `cond_expr_alt`

Evaluating conditionals

Example: `true ? 42 : 17;`

```
function eval_conditional(comp) {
    return is_truthy(evaluate(cond_expr_pred(comp)))
           ? evaluate(cond_expr_cons(comp))
           : evaluate(cond_expr_alt(comp));
}
```

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    return is_truthy(evaluate(cond_expr_pred(comp)
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const is_truthy = x => is_boolean(x) ? x : error(
```

Evaluating conditionals

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We explain conditionals in the interpreted language using conditional expressions in the interpreting language.

Evaluating conditionals

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We explain conditionals in the interpreted language using conditional expressions in the interpreting language.

A cop-out? A stroke of genius? You decide!

Parsing sequences: an example

```
parse("1; 2; 3;");
```

returns

```
list("sequence",
     list(list("literal", 1),
          list("literal", 2),
          list("literal", 3))
```

Parsing sequences: an example

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parse("1; 2; 3;");
```

returns

```
list("sequence",
     list(list("literal", 1),
          list("literal", 2),
          list("literal", 3))
```

Syntax predicate: `is_sequence`
Selectors: `sequence_statements`, `first_statement`, `rest_statements`
More syntax predicates: `is_empty_sequence`, `is_last_statement`

Evaluating sequences

Example: `8 + 34; true ? 1 + 2 : 17;`

```
function eval_sequence(stmts)
{
  if (is_empty_sequence(stmts)) {
    return undefined;
  } else if (is_last_statement(stmts)) {
    return evaluate(first_statement(stmts));
  } else {
    const ignore =
             evaluate(first_statement(stmts));
    return eval_sequence(
                    rest_statements(stmts)); }
}
```

Evaluating sequences

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}
```

Another cop-out/stroke-of-genius: We explain sequences in the

Adding blocks and declarations

stmt	::=	⋯	
	|	{ *stmt* }	block
	|	`const` *name* = *expr* ;	constant declaration
expr	::=	⋯	
	|	*name*	name

Example:

```
const y = 4;
{
    const x = y + 7;
    x * 2;
}
```

Evaluating the language

```
function evaluate(comp, env) {
  return ...
         : is_name(comp)
         ? lookup_symbol_value(symbol_of_name(com
                               env)
         : is_block(comp)
         ? eval_block(comp, env)
         : is_declaration(comp)
         ? eval_declaration(comp, env)
         : error(comp, "Unknown component:");
}
```

Frames and environments

```
function make_frame(names, values) {
    return pair(names, values);
}
const frame_names = head;
const frame_values = tail;

function extend_environment(ns, vs, e) {
    return pair(make_frame(ns, vs), e);
}
const the_empty_environment = null;
const the_global_environment
                    = the_empty_environment;
```

Evaluating blocks

Example of block statement:

```
{ const x = y + 7; x * 2; }
```

```
function eval_block(component, env) {
    const body = block_body(component);
    const locals = scan_out_declarations(body);
    const unassigneds = list_of_unassigned(locals
    return evaluate(body,
                    extend_environment(locals,
                                       unassigned
                                       env));
}
```

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    const unassigneds = list_of_unassigned(locals
    return evaluate(body,
                    extend_environment(locals,
                                       unassigned
                                       env));
}
const list_of_unassigned =
 symbols => map(symbol => "*unassigned*", symbols
```

Scanning out declarations

Example of block statement:

```
{ const x = y; { const y = 2; } const z = x/2; x;
```

```
function scan_out_declarations(comp) {
    return is_sequence(comp)
           ? accumulate(
                 append,
                 null,
                 map(scan_out_declarations,
                     sequence_statements(comp)))
           : is_declaration(comp)
           ? list(declaration_symbol(comp))
           : null;
}
```

Evaluating declarations

Example: `const x = y + 7;`

```
function eval_declaration(comp, env) {
    assign_symbol_value(
      declaration_symbol(comp),
      evaluate(declaration_value_expression(comp),
               env),
      env);
    return undefined;
}
```

Assign a name to a value

Example: `const x = 8 + 34;`

$\Rightarrow$ `assign_symbol_value("x", 42, env)`

```
function assign_symbol_value(symbol, val, env) {
  function scan_write(symbols, vals) {
    return symbol === head(symbols)
        ? set_head(vals, val) // was: "*unassigned*"
        : scan_write(tail(symbols), tail(vals));
  }
  const frame = first_frame(env);
  return scan_write(frame_symbols(frame),
                    frame_values(frame));
}
```

Some more environment functions

```
function first_frame(env) {
    return head(env);
}

function enclosing_environment(env) {
    return tail(env);
}

function is_empty_environment(env) {
    return is_null(env);
}
```

Looking up a symbol

```
function lookup_symbol_value(name, env)
{
  function env_loop(env) {
    function scan_read(names, vals) {...}
    if (is_empty_environment(env)) {
        error(name, "Unbound name:");
    } else {
      const frame = first_frame(env);
      const value = scan_read(frame_names(frame),
                              frame_values(frame));
      if (value === "*unassigned*") {
        error(name, "Used before declared:");
      } else { return value;
} } }
```

Adding compound functions

stmt	::=	···	
	|	`function` *name* `(` *params* `)` *block*	function declaration
expr	::=	···	
	|	*expr*`(` *expr*$_1$`,` ... `,` *expr*$_n$`)`	function application
	|	*params* `=>` *block*	lambda expression

Example:

```
function fact(n) { // no need for return
    n === 1 ? 1 : n * fact(n - 1);
}
fact(5); // result: 120
```

Evaluating compound functions

```
function evaluate(comp, env) {
 return ...
   : is_lambda_expression(comp)
   ? make_function(lambda_parameter_symbols(comp),
                   lambda_body(comp), env)
   : is_function_declaration(comp)
   ? evaluate(function_decl_to_constant_decl(comp),
              env)
   : is_application(comp)
   ? apply(evaluate(function_expression(comp), env),
           list_of_values(arg_expressions(comp), env))
   : error(comp, "Unknown component:");
}
```

Function objects

Example: `x => x + y`

```
function make_function(parameters, body, env) {
    return list("compound_function",
                parameters, body, env);
}
```

Transformation of function declaration

```
function fact(n) {
    n === 1 ? 1 : n * fact(n - 1);
}
// becomes
const fact = n => { n===1 ? 1 : n * fact(n - 1);

function function_decl_to_constant_decl(comp) {
  return make_constant_declaration(
            function_declaration_name(comp),
            make_lambda_expression(
              function_declaration_parameters(comp
              function_declaration_body(comp)));
}
```

Function application

Example: `fact(n - 1)`

```
function apply(fun, args) {
  return is_primitive_function(fun)
         ? apply_primitive_function(fun, args)
         : is_compound_function(fun)
         ? evaluate(function_body(fun),
                    extend_environment(
                       function_parameters(fun),
                       args,
                       function_environment(fun))
         : error(fun, "Unknown function type:");
}
```

Declaring primitive functions

```
const primitive_functions =
  list(pair("math_sin", math_sin),
       ...
```

Declaring primitive functions

```
const primitive_functions =
  list(pair("math_sin", math_sin,
            ...
            // operator combinations can be treated
            // as primitive function applications
            pair("+"          , (x, y) => x + y),
            pair("-"          , (x, y) => x - y),
            ...));
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Declaring primitive functions

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const primitive_functions =
  list(pair("math_sin", math_sin,
        ...
        // operator combinations can be treated
        // as primitive function applications
        pair("+"          , (x, y) => x + y),
        pair("-"          , (x, y) => x - y),
        ...);
function setup_environment () {
    ...primitive_functions...
}
const the_global_environment =
    setup_environment();
```

Applying primitive functions

```
function apply_primitive_function(fun, arglist) {
    return apply_in_underlying_javascript(
                primitive_implementation(fun),
                arglist);
}
```

Return statements in JavaScript

The Problems

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Return statements in JavaScript

The Problems

- Functions that do not evaluate a return statement must return `undefined`
- Evaluation of a return statement *anywhere* in the function body will return from the function with the result of evaluating the return expression

Adding return statements

$$\begin{array}{rcll} \textit{stmt} & ::= & \cdots & \\ & & \mid \texttt{return}\ \textit{expr}\ \texttt{;} & \text{return statement} \end{array}$$

Example:

```
function fact(n) {
    return n === 1 ? 1 : n * fact(n - 1);
}
fact(5);
```

Evaluating compound functions

```
function evaluate(comp, env) {
 return ...
   : is_return_statement(comp)
   ? eval_return_statement(component, env)
   : error(comp, "Unknown component:");
}
```

Handling return statements

Example: `return n * fact(n - 1);`

```
function eval_return_statement(stmt, env) {
    return make_return_value(
        evaluate(return_statement_expression(stmt),
                 env));
}
function make_return_value(content) {
    return list("return_value", content);
}
function is_return_value(value) {
    return is_tagged_list(value, "return_value");
}
```

Handling return values in sequences

```
function eval_sequence(stmts, env)                    {
  if (is_empty_sequence(stmts)) {
    return undefined;
  } else if (is_last_statement(stmts)) {
    return evaluate(first_statement(stmts), env);
  } else {
    const first_stmt_value =
            evaluate(first_statement(stmts),env);
    if (is_return_value(first_stmt_value)) {
      return first_stmt_value;
    } else {
      return eval_sequence(
                    rest_statements(stmts),env);
  } }                                                  }
```

Handling return values in apply

```
function apply(fun, args) {
  ...
  const result = evaluate(...body...);
  if (is_return_value(result)) {
    return return_value_content(result);
  } else {
    return undefined;
  } ...
}
```

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  communicating the computational process called "environment model"
- Frames and environment, clarified as *data types*
- Demystify environments: lists of pairs!
- Demystify function objects: lists!
- `evaluate`—`apply` loop