Building Interpreters: Recap

CS 440: Programming Languages
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HW2

- Due tonight, 11:59pm (can take <= 2 late days as usual)
- For hof.ml and trees.ml:
  - You may not write **any** recursive (including tail-recursive) functions, except on the bonus question (and copy/pasting tree_fold)
- For all parts:
  - You can use any operators or library functions we've seen, as long as it isn't just what you're supposed to implement.
  - Examples of what's allowed: ^, @, List.init (will be very useful)
  - Not allowed: List.concat for implementing concatenate

Midterm: Thursday, 3/2

- In-class, 75 minutes
- Covers Lectures 0-13 (through today), Homeworks 0-2

Non-exhaustive list of topics

- Types of programming languages
- Interpreters vs. compilers
- Structure of an interpreter/compiler
- OCaml programming
  - Types, expressions, evaluation, (tail) recursion
  - Algebraic data types
  - Higher-order functions
- Interpreters
  - Environments

Format

- 4-5 (multi-part) questions
  - Short answer, some small programming questions

Other info

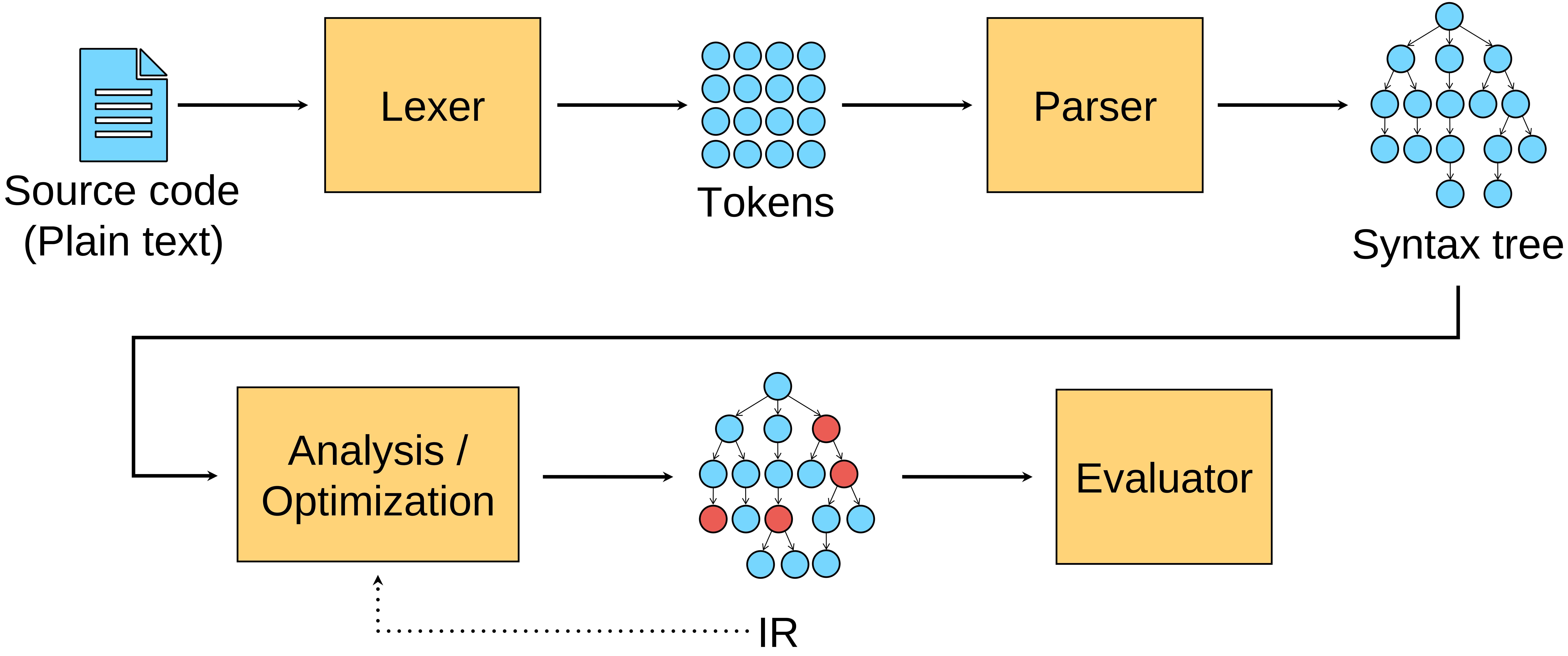
- Write in blue or black pen only (**no pencil**)
  - I reserve the right to deduct 5 points from exams written in pencil
- You can bring one double-sided 8.5x11” sheet of notes
  - Written or typed, can contain anything you want
- I’ll give you type signatures for the usual HOFs
  - Anything else you want? Let me know on Discord by tomorrow

Other info (continued)

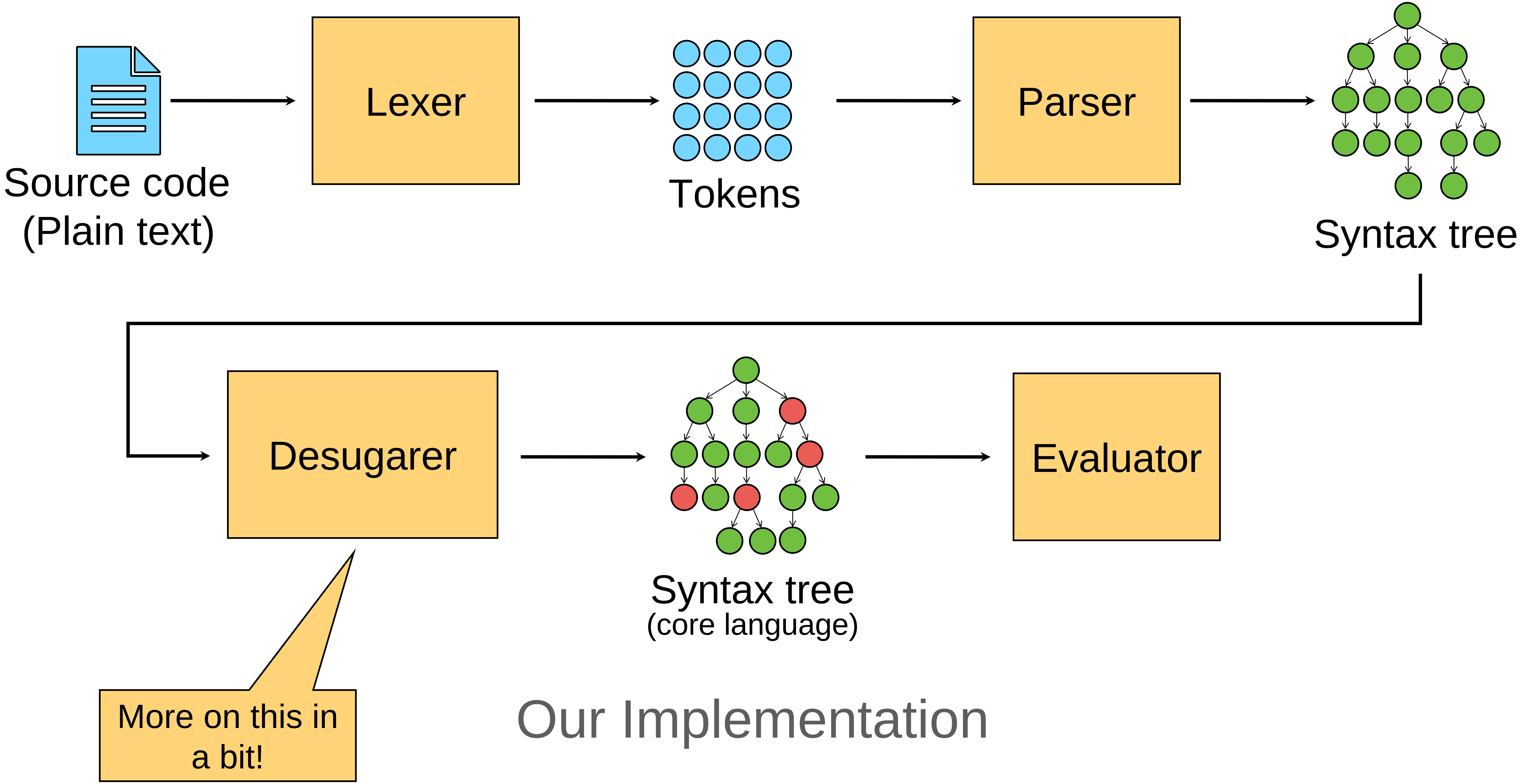
- I’ll post a practice exam soon

- Instead of Thursday office hours next week, I’ll have a Zoom review session Wed., 3/1 11-12

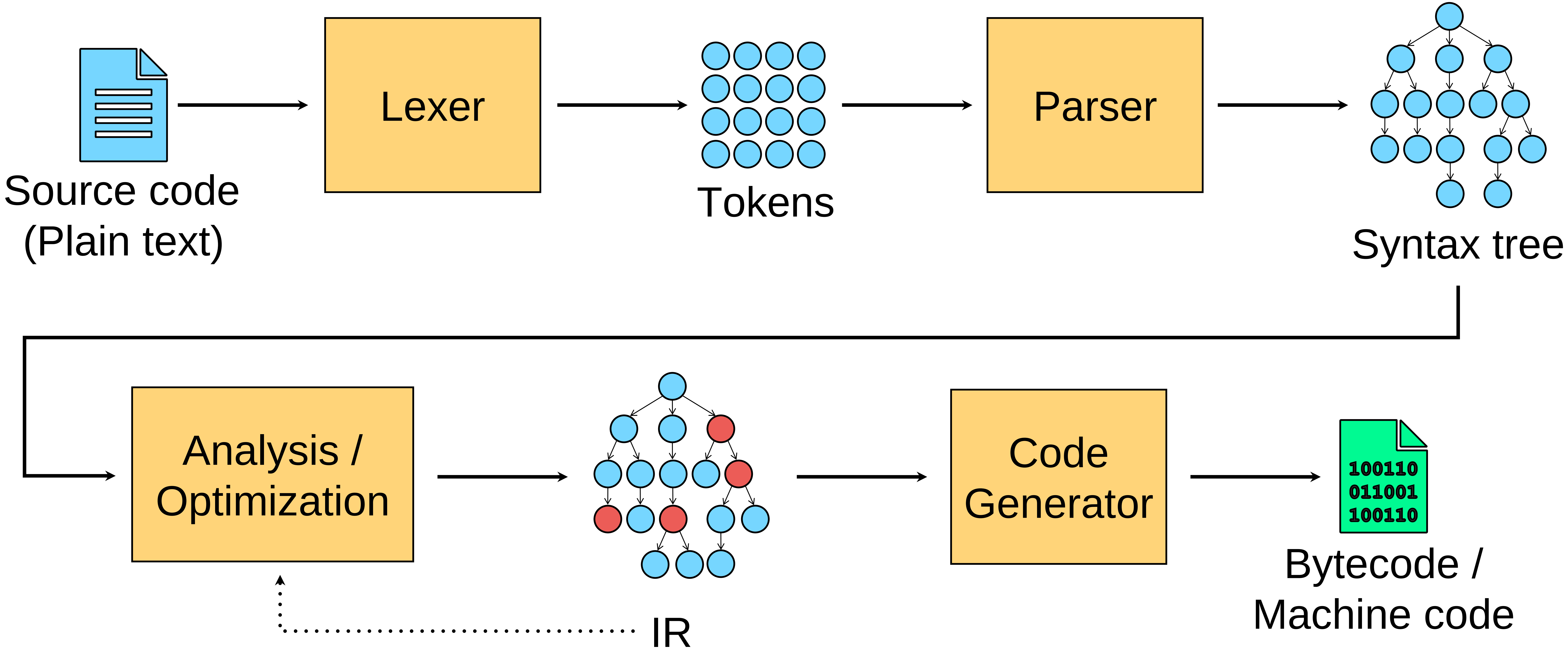
§ Overview



“Traditional” Interpreter Workflow



Our Implementation



Compilation Workflow

- Some implementation details

Identifier bindings

- let and fun forms bind identifiers within specific scopes
- An expression's *environment* comprises all bindings in effect when it is evaluated

```
let x = 44 in
  let y = 10 in
    x * y
```

```
let f = fun x -> x * 10
in
f 44
```

Identifier bindings

- We use an association list to represent an environment
  - E.g., [(x, ref 44); (y, ref 10)]
  - *Immutable structure*: bindings are prepended when recursing
  - Bindings may be mutably updated to allow backpatching

Identifier bindings

eval
env=[]

```
let x = 44 in
    let y = 10 in
        x * y
```

eval
env=[(x, ref 44)]

eval
env=[(y, ref 10); (x; ref 44)]

Identifier bindings

eval
env=[]

```
let x = 44 in
  let y = 10 in
    let x = 54 in
      x * y
```

eval
env=[(x, ref 44)]

eval
env=[(y, ref 10); (x; ref 44)]

eval
env=[(x, ref 54); (y, ref 10);
~~(x; ref 44)~~]
(shadowed)

let/lambda equivalence

- Note that all let forms can be written as lambda applications!

```
let x = 44
in x * 10
```

⇔

```
(fun x -> x * 10) 44
```

```
let x = 44 in
let y = 3 + 7 in
x * y
```

⇔

```
(fun x y -> x * y) 44 (3 + 7)
```

Evaluation strategies

- Question: **when** do we evaluate expressions in binding forms?
  - E.g., `let x = 1 + 2 in …`

    `(fun x -> …) (1 + 2)`

  - Two general strategies: **Eager** and **Lazy**

Eager evaluation

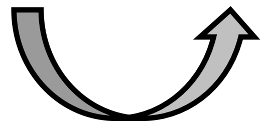
- Evaluate *before* binding the identifier
    - aka **call-by-value**: evaluated “value” is passed as arg to function

Lazy evaluation

- Evaluate the expression *only when needed*
  - aka **call-by-name**: un-evaluated expression "name" is passed
- An efficient version may cache (memoize) evaluated results instead of re-evaluating

let x = 1 + 2 in x + x + 4
(1 + 2) + (1 + 2) + 4
3 + (1 + 2) + 4
3 + 3 + 4
10

let x = 1 + 2 in x + x + 4
(1 + 2) + (1 + 2) + 4
3 + 3 + 4



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Eager vs. Lazy

- Eager evaluation is much more common in modern languages
  - More predictable behavior; easier to analyze program requirements
  - Often more efficient than a non-memoizing lazy evaluator
- Lazy evaluation may avoid doing unnecessary work (e.g., unreferenced identifiers in a function)
  - Control flow can be implemented via regular functions
  - Infinite / partially defined data structures are easy to define

Control flow with functions

```
type my_bool = True | False

let my_if (e: my_bool) (if_b: ‘a) (else_b: ‘a) =
  match e with
  | True -> if_b
  | False -> else_b

my_if True (1 + 2) (42 / 0)
```

⇓

```
my_if True 3 !!!!
```

Control flow with functions - Lazy

```
type my_bool = True | False

let my_if (e: my_bool) (if_b: ‘a) (else_b: ‘a) =
  match e with
  | True -> if_b
  | False -> else_b

my_if True (1 + 2) (42 / 0)
```

```
match True with True -> 1 + 2 | False -> 42 / 0
```

```
1 + 2
```

Scope selection

- Question: **which bindings** (for free variables) are used when evaluating a function (lambda)?
  - E.g.,

```
let f = let x = 44 in
            fun y ->
              x * y
in
let x = 33 in
 f 10
```

- Two strategies: **Dynamic** and **Lexical**

Dynamic binding

- Use the scopes in effect where the function is **called**
  - I.e., free variables are looked up in the *dynamic environment*

```
let f = let x = 5 in
            fun y -> x * y
in
  (let  x = 4 in f 10)
  + (let x = 3 in f 10)
```

> 70

Lexical binding

- Use the scopes in effect where the function is **defined**
  - I.e., a function captures or “closes over” bindings in its *lexical environment*
  - Lexically bound functions = **Closures**

```
let f = let x = 5 in
          fun y -> x * y
in
  (let  x = 4 in f 10)
  + (let x = 3 in f 10)
```

> 100

Closure implementation

- A closure couples a function with its lexical environment
- An efficient version would only keep required bindings
- Critical for languages with *first-class functions*
  - Functions may outlive their defining environment, but need to hang onto bindings!

Desugaring

- Question: how to add syntactic elements (and associated semantics)?
- Option 1: update parser & evaluator — all syntax is first class
- Option 2: translate new syntactic elements into **core language**
  - Performed during “desugaring” passes (syntactic sugar → core syntax)
  - Keeps core language small and easy to reason about / test!

Desugaring

- E.g., `fun x y z -> body …`

desugar

(can also desugar let -> application)

```
fun x ->
  fun y ->
    fun z -> body
```

Short-circuiting and/or

- `if x > 0 && y / x > 5 then 1 else 2`
- Remember eval case for `EBinop (e1, o, e2)`:

```
let v1 = eval_expr e1 env in
let v2 = eval_expr e2 env in
eval_op o v1 v2
```

eval_expr (EBinop (x > 0, And, y / x > 5)) ?

Short-circuiting and/or

- `if x > 0 && y / x > 5 then 1 else 2`

desugar

- `if if x > 0 then y / x > 5 else false then 1 else 2`

What did we leave out?

- Parsing!
- Language independent intermediate representations (e.g., LLVM)
- Optimizations (e.g., lean/fast environments, efficient execution)
- Memory management
- Code generation (transpiling, bytecode/machine code generation)
- Take **CS 443: Compiler Construction!**