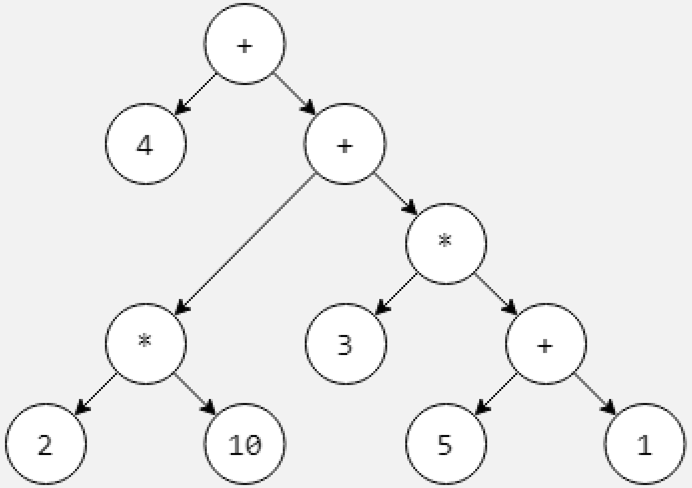
UMass Boston Computer Science

CS450 High Level Languages (section 2)

ASTs and Interpreters

Monday, November 4, 2024

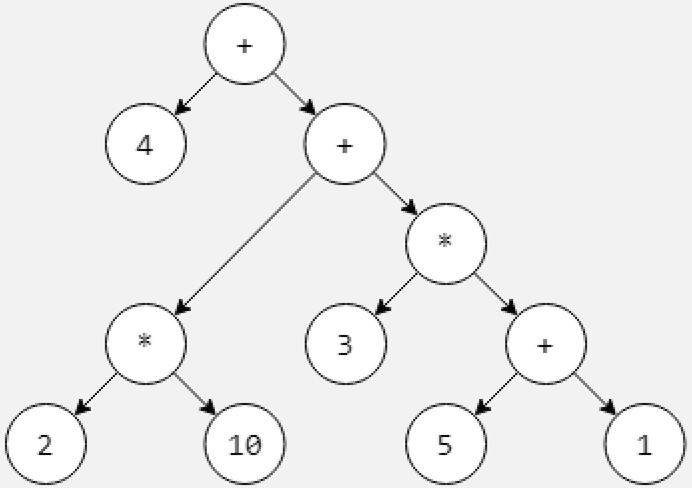


Logistics

- HW 9 “out”
  - See: **in-class work 11/4** and **11/6**
  - <u>due:</u> **Mon 11/11 12pm (noon) EST**

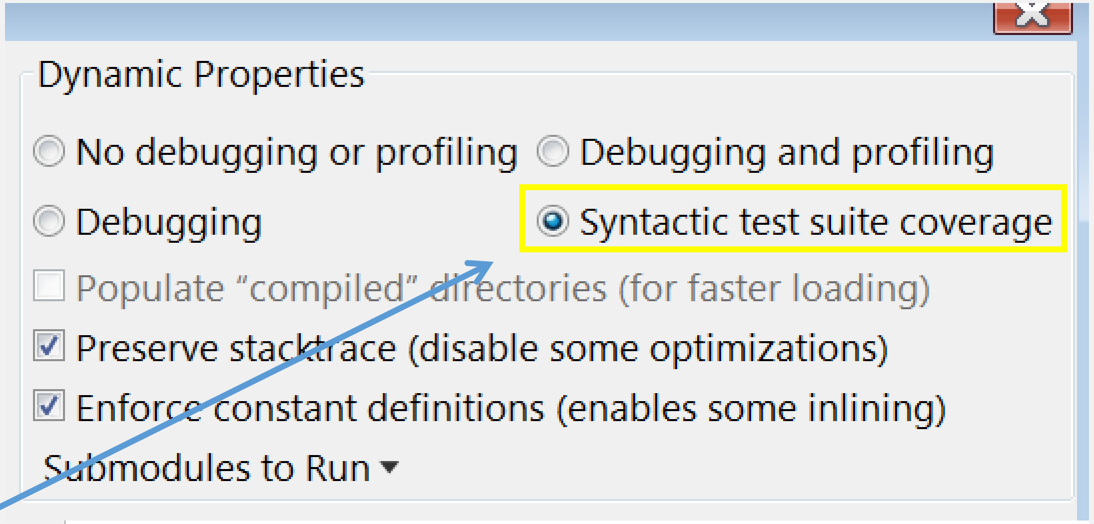
- HW 10 – extension of “hw9”
  - Out: **Tue 11/5**
  - <u>due:</u> **Mon 11/18 12pm (noon) EST**

- **no lecture:** Veteran’s Day Mon 11/11



HW Minimum Submission Requirements

- “`main`” runs without errors
- Tests run without errors
- 100% (Test / Example) “Coverage”
  - In “Choose Language” Menu
  - NOTE: only works with single files



This code was not run

```
;; YCoord is either
;; - before target
;; - in target
;; - after target
;; - out of scene
(define (PENDING-Note? n) (PENDING? (Note-state n)))
(define (HIT-Note? n) (HIT? (Note-state n)))
(define (MISSED-Note? n) (MISSED? (Note-state n)))
(define (OUTOFSCENE-Note? n) (OUTOFSCENE? (Note-state n)))
(define out-Note? OUTOFSCENE-Note?)

;; NEW
;; A WorldState is a List<Note>

(define (num-Notes w) (length w))
```

HW Minimum Submission Requirements

- “`main`” runs without errors
- Tests run without errors

Code should <u>never</u> get into a state where this is true!

Incremental programming!

Function Design Recipe

Previously

1. **Name**
2. **Signature** – <u>types</u> of the **function input(s)** and **output**
3. **Description** – <u>explain</u> (in **English prose**) the **function behavior**
4. **Examples** – <u>show</u> (using `rackunit`) the **function behavior**
5. **Template** – <u>sketch out</u> the **function structure** (using input's **Data Definition**)
6. **Code** – <u>implement</u> the **rest of the function** (arithmetic)
7. **Tests** – <u>check</u> (using `rackunit`) the **function behavior**

Incremental Programming

1. **Name**
2. **Signature** – <u>types</u> of the **function input(s)** and **output**
3. **Description** – <u>explain</u> (in **English prose**) the **function behavior**
4. **Examples** – <u>show</u> (using `rackunit`) the **function behavior**
5. **Template** – <u>sketch out</u> the **function structure** (using input's **Data Definition**)
6. **Code** – <u>implement</u> the **rest of the function** (arithmetic)

   Start: **by filling in with "placeholders"**
7. **Tests** – <u>check</u> (using `rackunit`) the **function behavior**

Code should <u>never</u> be crashing!

Incremental Programming

1. **Name**
2. **Signature** – types of the function input(s) and output
3. **Description** – explain (in English prose) the function behavior
4. **Examples** – show (using `rackunit`) the function behavior
5. **Template** – sketch out the function structure (using input's Data Definition)
6. **Code** – implement the rest of the function (arithmetic)
7. **Tests** – check (using `rackunit`) the function behavior

This way: always know there the "bug" is

Then: make small code changes and test immediately

Code should never be crashing!

Tests (and example tests) should always be passing!

Previously

Intertwined Data Definitions

- Come up with a Data Definition for …
- … valid Racket Programs

Basic Valid Racket Programs

- 1
- "one"
- `(+ 1 2)`

```
;; A RacketProg is a:
;; - Number
;; - String
```

```
;; - ???
```

Valid Racket Programs

- 1
- “one”
- (+ 1 2)

```
;; A RacketProg is a:
;; - Atom
```

```
;; - ???
```

```
;; An Atom is one of:
;; - Number
;; - String
```

Valid Racket Programs

- `(+ 1 2)` List of ... atoms?

"symbol"

```
;; A RacketProg is a:
;; - Atom
;; - List<Atom> ???
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

Valid Racket Programs

- ```
  (* (+ 1 2)
     (- 4 3))
  ```
  Tree?

- ```
  (* (+ 1 2)
     (- 4 3)
     (/ 10 5))
  ```

Each tree “node” is a list, of ... RacketProgs ??

But: how many values does each node have?? Unknown!

```
;; A RacketProg is a:
;; - Atom
```

;; - ~~List<Atom> ???~~

```
;; - Tree<???>
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

Valid Racket Programs

- ```
  (* (+ 1 2)
     (- 4 3))
  ```
- ```
  (* (+ 1 2)
     (- 4 3)
     (/ 10 5))
  ```

Tree?

Each tree "node" is a list, of … RacketProgs ??

But: how many values does each node have??

```
;; A RacketProg is a:
;; - Atom
;; - ProgTree
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

```
;; A ProgTree is one of:
;; - empty
;; - (cons RacketProg ProgTree)
```

Recursive Data Def!

Valid Racket Programs

Also, **Intertwined** Data Defs!

```
;; A RacketProg is a:
;; - Atom
;; - ProgTree
```

```
;; A ProgTree is one of:
;; - empty
;; - (cons RacketProg ProgTree)
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

Intertwined Data

- A set of Data Definitions that reference each other
- Templates should be defined together ...

```
;; A RacketProg is a:
;; - Atom
;; - ProgTree
```

```
;; A ProgTree is one of:
;; - empty
;; - (cons RacketProg ProgTree)
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

Intertwined Data

- A <u>set</u> of Data Definitions that <u>reference each other</u>
- <u>Templates</u> should be <u>defined together</u> …
  - … and should <u>reference each other's templates</u> (when needed)

```
;; A RacketProg is one of:
;; - Atom
;; - ProgTree
(define (prog-fn p) ...)
```

```
;; A ProgTree is one of:
;; - empty
;; - (cons RacketProg ProgTree)
(define (ptree-fn t) ...)
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
(define (atom-fn a) ...)
```

???

Intertwined Templates

```
;; A RacketProg is one of:
;; - Atom
;; - ProgTree
```

```
(define (prog-fn s)
  (cond
   [(atom? s) ... (atom-fn s) ...]
   [else  ... (ptree-fn s) ...]))
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

```
(define (atom-fn a)
 (cond
   [(number? a) ... ]
   [(string? a) ... ]
   [else ... ]))
```

```
;; A ProgTree is one of:
;; - empty
;; - (cons RacketProg ProgTree)
```

```
(define (ptree-fn t)
  (cond
   [(empty? t) ...]
   [else  ... (prog-fn (first t)) ... (ptree-fn (rest t)) ...]))
```

Intertwined data have intertwined templates!

A "Racket Prog" = S-expression!

```
;; A ~~RacketProg~~ Sexpr is one of:
;; - Atom
;; - ProgTree
```

```
(define (sexpr-fn s)
  (cond
   [(atom? s) ... (atom-fn s) ...]
   [else  ... (ptree-fn s) ...]))
```

```
;; A ProgTree is one of:
;; - empty
;; - (cons ~~RacketProg~~ Sexpr ProgTree)
```

```
(define (ptree-fn t)
  (cond
   [(empty? t) ...]
   [else  ... (sexpr-fn (first t)) ... (ptree-fn (rest t)) ...]))
```

```
;; An Atom is one of:
;; - Number
;; - String
;; - Symbol
```

```
(define (atom-fn a)
 (cond
   [(number? a) ... ]
   [(string? a) ... ]
   [else ... ]))
```

Counting Symbols

```
;; count : Symbol Sexpr -> Nat
;; Computes the number of times the given
;; symbol appears in the given s-expression
(define (count sym se)
  (cond
   [(atom? s) ... (atom-fn s) ...]
   [else  ... (ptree-fn s) ...]))
```

```
;; count-atom : Symbol Atom -> Nat
(define (count-atom sym a)
 (cond
   [(number? a) ... ]
   [(string? a) ... ]
   [else ... ]))
```

```
;; count-ptree : Symbol ProgTree -> Nat
(define (count-ptree sym pt)
  (cond
   [(empty? pt) ...]
   [else  ... (sexpr-fn (first pt)) ... (ptree-fn (rest pt)) ...]))
```

Counting Symbols

```
;; count : Symbol Sexpr -> Nat
;; Computes the number of times the given
;; symbol appears in the given s-expression
(define (count sym se)
  (cond
   [(atom? s) (count-atom sym se)]
   [else (count-ptree sym se)]))
```

```
;; count-atom : Symbol Atom -> Nat
(define (count-atom sym a)
 (cond
   [(number? a) ... ]
   [(string? a) ... ]
   [else ... ]))
```

```
;; count-ptree : Symbol ProgTree -> Nat
(define (count-ptree sym pt)
  (cond
   [(empty? pt) ...]
   [else  ... (sexpr-fn (first pt)) ... (ptree-fn (rest pt)) ...]))
```

Counting Symbols

```
;; count : Symbol Sexpr -> Nat
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;; symbol appears in the given s-expression
```

```
(define (count sym se)
  (cond
   [(atom? s) (count-atom sym se)]
   [else (count-ptree sym se)]))
```

```
;; count-atom : Symbol Atom -> Nat
```

```
(define (count-atom sym a)
 (cond
   [(symbol? a)
    (if (symbol=? sym a) 1 0)  ]
   [else 0]))
```

```
;; count-ptree : Symbol ProgTree -> Nat
```

```
(define (count-ptree sym pt)
  (cond
   [(empty? pt) ...]
   [else  ... (sexpr-fn (first pt)) ... (ptree-fn (rest pt)) ...]))
```

Counting Symbols

```
;; count : Symbol Sexpr -> Nat
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;; symbol appears in the given s-expression
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```
(define (count sym se)
  (cond
   [(atom? s) (count-atom sym se)]
   [else (count-ptree sym se)]))
```

```
;; count-atom : Symbol Atom -> Nat
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(define (count-atom sym a)
 (cond
   [(symbol? a)
    (if (symbol=? sym a) 1 0)]
   [else 0]))
```

```
;; count-ptree : Symbol ProgTree -> Nat
```

```
(define (count-ptree sym pt)
  (cond
   [(empty? pt) 0]
   [else  ... (sexpr-fn (first pt)) ... (ptree-fn (rest pt)) ...]))
```

Counting Symbols

```
;; count : Symbol Sexpr -> Nat
;; Computes the number of times the given
;; symbol appears in the given s-expression
```

```
(define (count sym se)
  (cond
   [(atom? s) (count-atom sym se)]
   [else (count-ptree sym se)]))
```

```
;; count-atom : Symbol Atom -> Nat
```

```
(define (count-atom sym a)
 (cond
   [(symbol? a)
    (if (symbol=? sym a) 1 0)]
   [else 0]))
```

```
;; count-ptree : Symbol ProgTree -> Nat
```

```
(define (count-ptree sym pt)
  (cond
   [(empty? pt) 0]
   [else (+ (count sym (first pt))
            (count-ptree sym (rest pt)))]))
```

Syntax vs Semantics (Spoken Language)

Syntax

- Specifies: validity of language structures
  - E.g., **sentence** = **noun** (subject) + **verb** + **noun** (object)
- "the ball threw the child"
  - Syntactically: valid!
  - Semantically: ???

Semantics

- Specifies: meaning of language structures

Syntax vs Semantics (Programming Language)

Syntax

- Specifies: validity of language structures
  - E.g., ???

Semantics

- Specifies: meaning of language structures

Syntax vs Semantics (Programming Language)

Syntax

- Specifies: **validity** of ~~language structures~~ **programs!**
  - E.g., **valid Racket program = s-expressions**
  - E.g., **valid Python program = …**

Q: What is the "meaning" of a program?

A: The result from "running" it

Semantics

- Specifies: **meaning** of ~~language structures~~ **programs!**

How does a program "**run**"?

Running Programs: `eval`

```
;; eval : Sexpr -> Result
;; “runs” a given Racket program, producing a “result”
```

An **“eval” function turns** a **“program”** into a **“result”**

An **“eval” function** is **more generally called** an **interpreter**

(Programs are usually not directly interpreted)

More commonly**, a high-level program is first compiled** to a **lower-level language** (and then intrepreted)

Q: What is the “meaning” of a program?

A: The result from “running” it

How does a program “**run**”?

From Lecture 1

NOTE: This hierarchy is *approximate*

"high" level
(easier for humans to understand)

"declarative"

"imperative"

"low" level
(runs on cpu)

English	
Specification langs	Types? pre/post cond?
Markup (html, markdown)	tags
Database (SQL)	queries
Logic Program (Prolog)	relations
Lazy lang (Haskell, R)	Delayed computation
Functional lang (Racket)	Expressions (no stmts)
JavaScript, Python	"eval"
C# / Java	GC (no alloc, ptrs)
C++	Classes, objects
C	Scoped vars, fns
Assembly Language	Named instructions
Machine code	Binary

More commonly, **a high-level program is first compiled** to a **lower-level language** (and then intrepreted)

“high” level
(easier for humans to understand)

surface language

compiler

target language

“declarative”

“imperative”

“low” level
(runs on cpu)

- Specification langs
- Markup (`html, markdown`)
- Database (`SQL`)
- Logic Program (`Prolog`)
- Lazy lang (`Haskell, R`)
- Functional lang (`Racket`)
- JavaScript, Python
- C# / Java
- C++
- C
- Assembly Language
- Machine code

Common **target** languages:
- bytecode (e.g., JS, Java)
- assembly
- machine code

A **virtual machine** is just a **bytecode interpreter**

A (hardware) **CPU** is just a **machine code interpreter!**

surface language

input

```
while b ≠ 0:
    if a > b:
        a := a - b
    else:
        b := b - a
return a
```

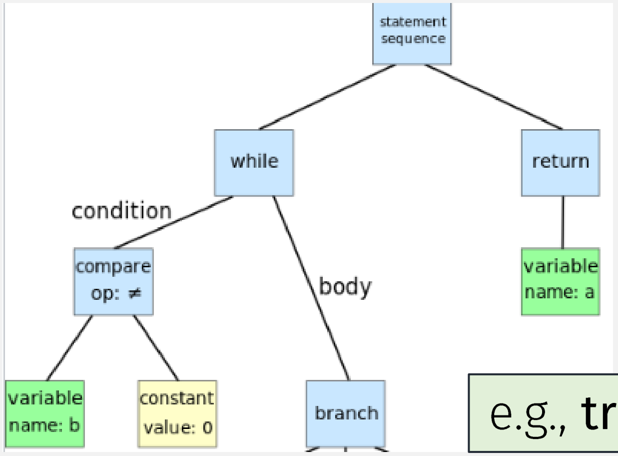
e.g., **string of chars** (less structure)

compiler

This itself is a program

target language

output



e.g., **tree** (more structure)

Semantics

- Specifies: **meaning of language <u>structures</u>**
- So: **to “run” a program, we need to see the structure first**

input

```
while b ≠ 0:
    if a > b:
        a := a - b
    else:
        b := b - a
return a
```

e.g., **string of chars** (less structure)

surface language

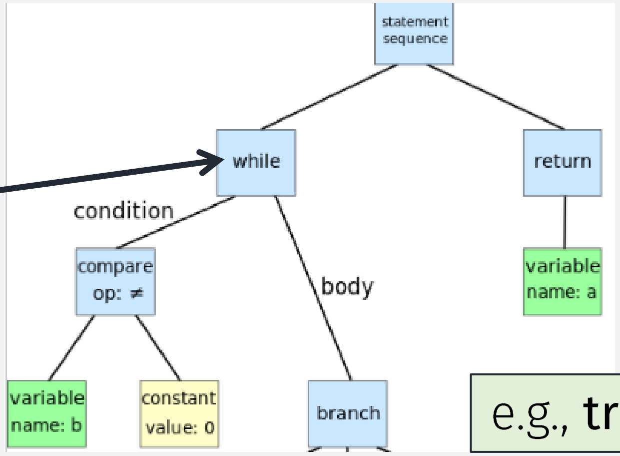
Compiler, step 1

= **parser**

(a **compiler** actually has <u>many steps</u> … take a compilers course!)

abstract syntax tree (AST)

output



e.g., **tree** (more structure)

These must have representations
(**data definitions!**)

SExpr

input

surface language

This itself is a program!

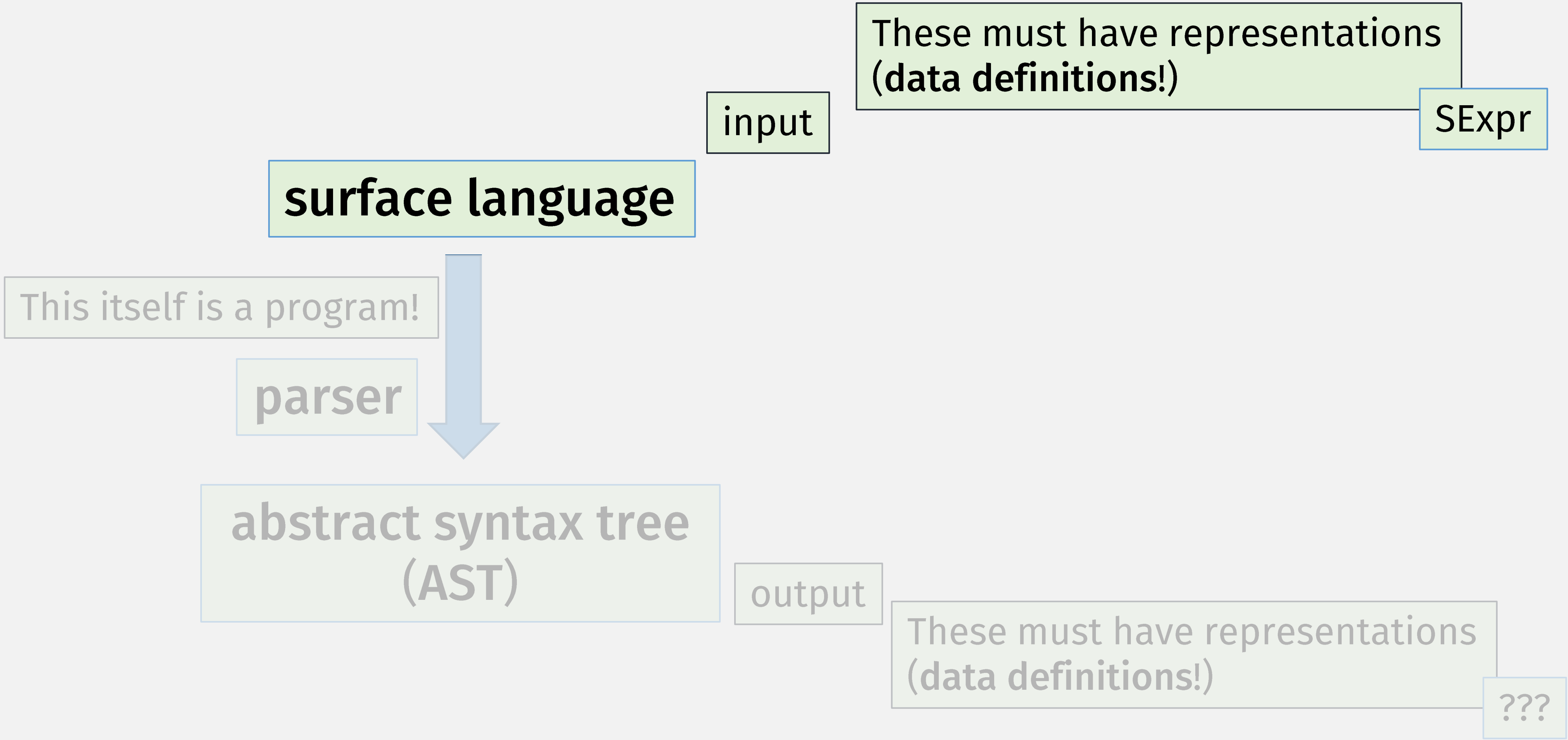
parser

**abstract syntax tree
(AST)**

output

These must have representations
(**data definitions!**)

???


These must have representations
(data definitions!)
input
SExpr
surface language
This itself is a program!
parser
abstract syntax tree
(AST)
output
These must have representations
(data definitions!)
???

These must have representations (**data definitions!**)

input

SExpr

surface language

```
;; A SimpleSexpr (Ssexpr) is one of:
;; - Number
;; - (list '+ Ssexpr Ssexpr)
;; - (list '- Ssexpr Ssexpr)
```

Data Definition Template

When a **Data Definition** is an **itemization** of **compound data** …

- **Template =**
  - cond to distinguish cases
  - “Getters” to extract pieces
  - recursive calls

```
;; A SimpleSexpr (Ssexpr) is one of:
;; - Number
;; - (list ‘+ Ssexpr Ssexpr)
;; - (list ‘- Ssexpr Ssexpr)
```

```
(define (ss-fn s)
  (cond
    [(number? s) … ]
    [(and (list? s) (equal? ‘+ (first s)))
     … (ss-fn (second s)) … (ss-fn (third s)) … ]
    [(and (list? s) (equal? ‘- (first s)))
     … (ss-fn (second s)) … (ss-fn (third s)) … ]))
```

Cond guards must distinguish the different cases

“getters”

Recursive call(s)

Interlude: pattern **match**ing (again)

When a **Data Definition** is an **itemization** of **compound data** …

- **Template =**
  - ~~cond to distinguish cases~~
  - **match** = cond + getters
  - recursive calls

```
;; A SimpleSexpr (Ssexpr) is one of:
;; - Number
;; - (list ‘+ Ssexpr Ssexpr)
;; - (list ‘- Ssexpr Ssexpr)
```

```
(define (ss-fn s)
  (match s
    [(? number?) … ]
    [`(+ ,x ,y)
      … (ss-fn x) … (ss-fn y) … ]
    [`(- ,x ,y)
      … (ss-fn x) … (ss-fn y) … ]))
```

Predicate pattern

“Quasiquote” pattern

Symbols match exactly

Match patterns

“Unquote” defines new variable name (for value at that position)

Interlude: pattern `match`ing (again)

- See Racket docs for the full pattern language

The grammar of *pat* is as follows, where non-italicized identifiers are recognized symbolically (i.e., not by binding).

pat ::=	*id*	match anything, bind identifier
|	(var *id*)	match anything, bind identifier
|	_	match anything
|	*literal*	match literal
|	(quote *datum*)	match `equal?` value
|	(list *lvp* ...)	match sequence of *lvps*
|	(list-rest *lvp* ... *pat*)	match *lvps* consed onto a *pat*
|	(list* *lvp* ... *pat*)	match *lvps* consed onto a *pat*
|	(list-no-order *pat* ...)	match *pats* in any order
|	(list-no-order *pat* ... *lvp*)	match *pats* in any order
|	(vector *lvp* ...)	match vector of *pats*
|	(hash-table (*pat* *pat*) ...)	match hash table
|	(hash-table (*pat* *pat*) ...+ *ooo*)	match hash table
|	(cons *pat* *pat*)	match pair of *pats*
|	(mcons *pat* *pat*)	match mutable pair of *pats*
|	(box *pat*)	match boxed *pat*
|	(*struct-id* *pat* ...)	match *struct-id* instance
|	(struct *struct-id* (*pat* ...))	match *struct-id* instance
|	(regexp *rx-expr*)	match string
|	(regexp *rx-expr* *pat*)	match string, result with *pat*
|	(pregexp *px-expr*)	match string
|	(pregexp *px-expr* *pat*)	match string, result with *pat*
|	(and *pat* ...)	match when all *pats* match
|	(or *pat* ...)	match when any *pat* match
|	(not *pat* ...)	match when no *pat* matches
|	(app *expr* pats ...)	match (*expr* value) output values to *pats*
|	(? *expr* *pat* ...)	match if (*expr* value) and *pats*
|	(quasiquote *qp*)	match a quasipattern
|	*derived-pattern*	match using extension

Interlude: pattern `match`ing (again)

When a **Data Definition** is an **itemization** of **compound data** ...

- **Template** =
  - ~~cond to distinguish cases~~
  - `match` = cond + getters
  - recursive calls

`match` can be more concise and readable

```
(define (ss-fn s)
  (match s
    [(? number?) … ]
    [`(+ ,x ,y)
      … (ss-fn x) … (ss-fn y) … ]
    [`(- ,x ,y)
      … (ss-fn x) … (ss-fn y) … ]))
```

vs

```
(define (ss-fn s)
  (cond
    [(number? s) … ]
    [(and (list? s) (equal? '+ (first s)))
     … (ss-fn (second s)) …
     … (ss-fn (third s)) … ]
    [(and (list? s) (equal? '- (first s)))
     … (ss-fn (second s)) …
     … (ss-fn (third s)) … ]))
```

These must have representations (**data definitions!**)

input

SExpr

surface language

This itself is a program!

parser

abstract syntax tree (AST)

```
;; A SimpleSexpr (Ssexpr) is one of:
;; - Number
;; - (list ‘+ Ssexpr Ssexpr)
;; - (list ‘- Ssexpr Ssexpr)
```

output

These must have representations (**data definitions!**)

???

surface language

This itself is a program!

parser

abstract syntax tree (AST)

```
;; An AST is one of:
;; - (num Number)
;; - (plus AST AST)
;; - (minus AST AST)
;; Interp: Tree structure for Ssexpr prog
(struct num [val])
(struct plus [left right])
(struct minus [left right])
```

output

These must have representations (**data definitions!**)

???

```
;; An AST is one of:
;; - (num Number)
;; - (plus AST AST)
;; - (minus AST AST)
;; Interp: Tree structure for Ssexpr prog
(struct num [val])
(struct plus [left right])
(struct minus [left right])
```

- **Template =**

```
(define (ast-fn p)
  (cond
    [(num? p) … ]
    [(plus? p)  … (ast-fn (plus-left p))
                … (ast-fn (plus-right p))  … ]
    [(minus? p)  … (ast-fn (minus-left p))
                 … (ast-fn (minus-right p))  … ]))
```

```
;; An AST is one of:
;; - (num Number)
;; - (plus AST AST)
;; - (minus AST AST)
;; Interp: Tree structure for Ssexpr prog
(struct num [val])
(struct plus [left right])
(struct minus [left right])
```

- **Template** (with `match`) =

(define (ast-fn p)
  (~~cond~~ match p

```
    [(num n) … ]
    [(plus x y) … (ast-fn x) …
                … (ast-fn y) … ]
    [(minus x y) … (ast-fn x) …
                   (ast-fn y) … ])
```

Struct name

Struct patterns

Extracts and names fields

In-class Coding 11/4 #1 (HW9): parser

```
;; parse: SimpleSexpr -> AST
;; Converts a (simple) S-expression to language AST
```

```
;; A SimpleSexpr (Ssexpr) is a:
;; - Number
;; - (list ‘+ Ssexpr Ssexpr)
;; - (list ‘- Ssexpr Ssexpr)
```

```
;; An AST is one of:
;; - (num Number)
;; - (plus AST AST)
;; - (minus AST AST)
;; Interp: Tree structure for Ssexpr
(struct num [val])
(struct plus [left right])
(struct minus [left right])
```

In-class Coding 11/4 #2 (HW9): eval

```
;; eval-ast: AST -> Result
;; computes the result of given program AST
```

```
;; A Result is a … ???
```

```
;; An AST is one of:
;; - (num Number)
;; - (plus AST AST)
;; - (minus AST AST)
;; Interp: Tree structure for Ssexpr
(struct num [val])
(struct plus [left right])
(struct minus [left right])
```

```
;; eval-ssexpr : Ssexpr -> Result
(define eval-ssexpr
  (compose eval-ast parse))
```