UMass Boston Computer Science

CS450 High Level Languages (section 2)

Variables and Environments in CS450 Lang

Monday, November 18, 2024

Logistics

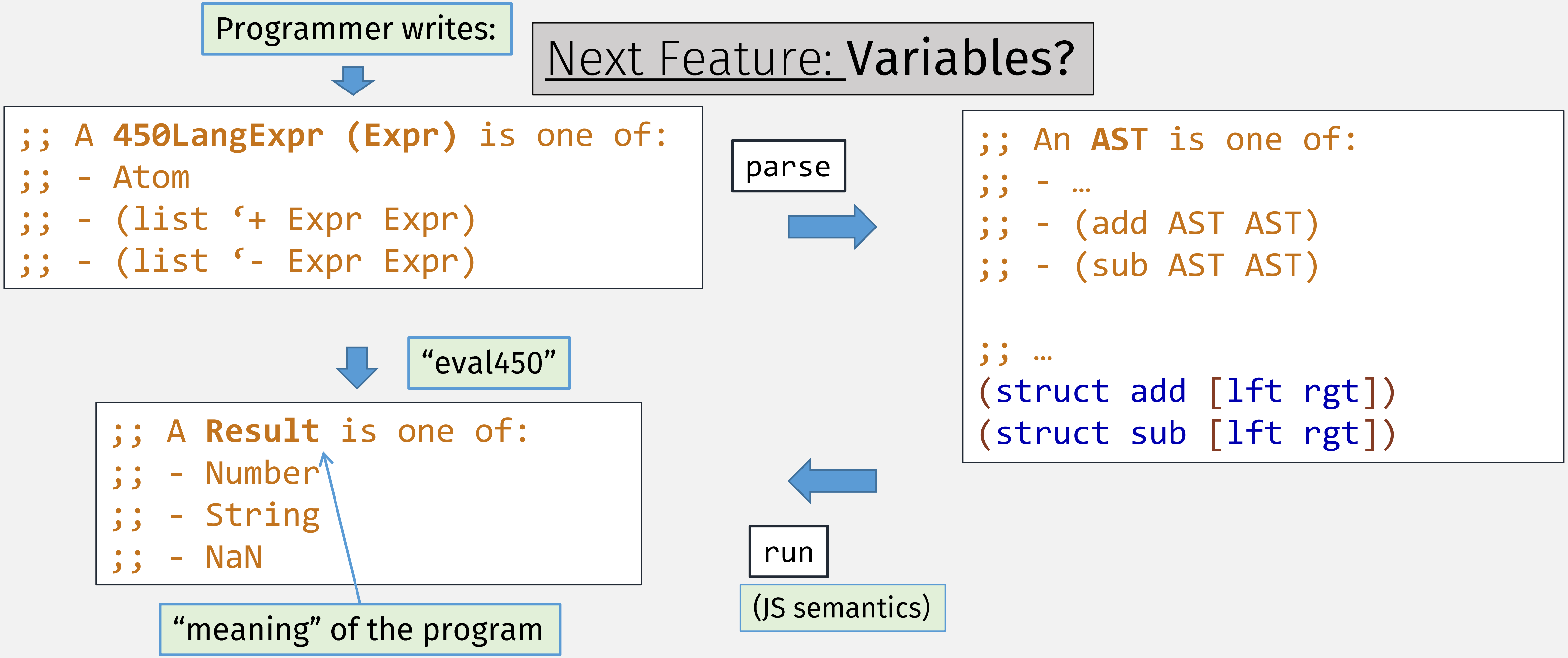
- HW 10 in
  - ~~due: Mon 11/18 12pm noon EST~~

- HW 11 out
  - due: Mon 11/25 12pm noon EST

- HW 12
  - out: Mon 11/25 12pm noon EST
  - due: Wed 12/4 12pm noon EST

Last Time

Introducing: The “CS450” Programming Lang!



Programmer writes:

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - (list ‘+ Expr Expr)
;; - (list ‘- Expr Expr)
```

Next Feature: Variables?

parse

```
;; An AST is one of:
;; - …
;; - (add AST AST)
;; - (sub AST AST)

;; …
(struct add [lft rgt])
(struct sub [lft rgt])
```

run

(JS semantics)

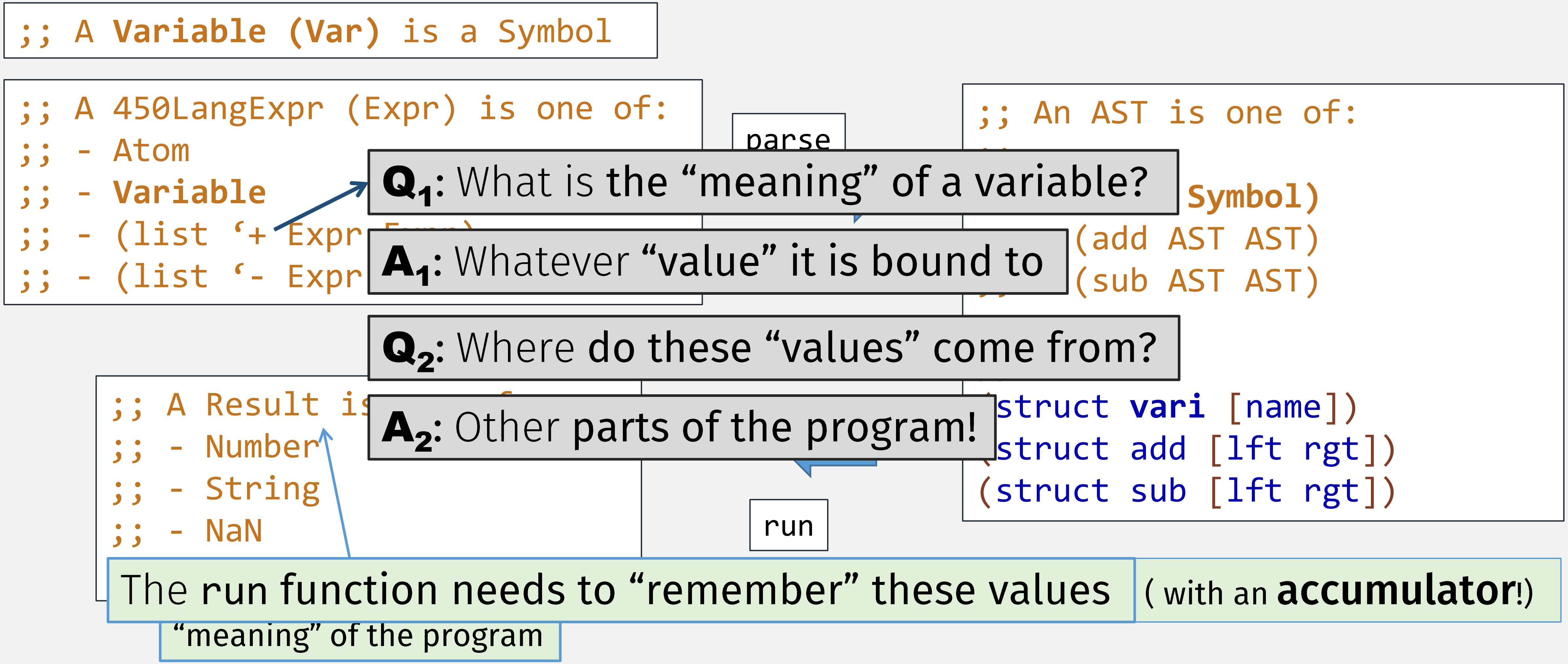
“eval450”

```
;; A Result is one of:
;; - Number
;; - String
;; - NaN
```

“meaning” of the program

Last Time

Adding Variables



```
;; A Variable (Var) is a Symbol
```

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list '+ Expr
;; - (list '- Expr
```

```
;; An AST is one of:
                  Symbol)
               (add AST AST)
               (sub AST AST)

 struct vari [name])
 struct add [lft rgt])
(struct sub [lft rgt])
```

```
;; A Result is
;; - Number
;; - String
;; - NaN
```

Q$_1$: What is the "meaning" of a variable?

A$_1$: Whatever "value" it is bound to

Q$_2$: Where do these "values" come from?

A$_2$: Other parts of the program!

The run function needs to "remember" these values

(with an **accumulator**!)

"meaning" of the program

run, with an accumulator

```
;; run: AST -> Result
;; Computes result of running a CS450 Lang program AST
```

```
(define (run p)
  ;; accumulator acc : Environment
  ;; invariant: Contains variable values … currently in-scope
  (define (run/acc p acc)
    (match p
     [(num n) n]
     [(add x y) (450+ (run/acc x) (run/acc y))]))
 (run/acc p  ???  ))
```

Environments

- A **data structure** that “**associates**” **two things** (`var`, `val`) **together**
  - E.g., **maps, hashes,** etc
  - For simplicity, let’s use **list-of-pairs**

```
;; An Environment is one of:
;; - empty
;; - (cons (list Var Result) Environment)

;; interpretation: a runtime environment for
;; (i.e., gives meaning to) cs450-lang variables

;; if there are duplicates,
;; vars at front of list shadow those in back
```

Environments

- A **data structure** that “**associates**” **two things** (`var`, `val`) **together**
  - E.g., **maps, hashes,** etc
  - For simplicity, let’s use **list-of-pairs**

```
;; An Environment is one of:
;; - empty
;; - (cons (list Var Result) Environment)
```

- Needed operations:
  - `env-add    : Env Var Result -> Env`
  - `env-lookup : Env Var -> Result`

Environments

```
;; An Environment is one of:
;; - empty
;; - (cons (list Var Result) Environment)
```

```
;; interpretation: a runtime environment
;; gives meaning to cs450lang variables
```

```
;; for duplicates, vars at front of
;; list shadow those in back
```

- Needed operations:
  - `env-add    : Env Var Result -> Env`
  - `env-lookup : Env Var -> Result`

Think about examples where this happens!

env-add examples

```
;; env-add: Env Var Result -> Env
```

```
(check-equal? (env-add ‘() ‘x 1)
              ‘((x 1)) )       ; empty
```

```
(check-equal? (env-add ‘((x 1)) ‘y 2)
              ‘((y 2) (x 1)) ) ; add new var
```

```
(check-equal? (env-add ‘((x 1)) ‘x 3)
              ‘((x 3) (x 1)) ) ; add shadowed var
```

Env template

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
(define (env-fn env … )
  (cond
   [(empty? env) … ]
   [else
    (match-let
        ([(cons (list x result) rest-env) env])
      … x … result … (env-fn rest-env … ) … ]))
```

2 cases

2nd case extracts components of compound data

Env template

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
(define (env-fn env … )
  (cond
   [(empty? env) … ]
   [else
    (match-let
      ([(cons (list x result) rest-env) env])
      ([`((,x ,result) . rest-env) env])
     … x … result … (env-fn rest-env … ) … ]))
```

2 cases

cons “rest” pattern

Quasiquote pattern

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
;; env-add: Env Var Result -> Env
```

```
(define (env-add env new-x new-res)
  (cond
   [(empty? env) … ]
   [else
    (match-let
        ([(cons (list x result) rest-env) env])
        ([`((,x ,result) . rest-env) env])
      … x … result …(env-add rest-env … ) … ]))
```

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
;; env-add: Env Var Result -> Env
(define (env-add env new-x new-res)
  (cond
   [(empty? env) (cons (list new-x new-res) env)]
   [else   … ]))
```

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
;; env-add: Env Var Result -> Env
```

```
(define (env-add env new-x new-res)
  (cond
   [(empty? env) (cons (list new-x new-res) env)]
   [else         (cons (list new-x new-res) env)]))
```

Sometimes you start with template … but don’t use it!

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
;; env-add: Env Var Result -> Env
(define (env-add env new-x new-res)
  (cons (list new-x new-res) env))
```

Sometimes you start with template … but don’t use it!

env-lookup examples

```
;; env-lookup: Env Var -> Result
```

```
(check-equal? (env-lookup ‘((y 2) (x 1)) ‘x)
              1 ) ; no dup
```

```
(check-equal? (env-lookup ‘((x 2) (x 1)) ‘x)
              2 ) ; duplicate
```

```
(check-equal? (env-lookup ‘() ‘x)
         UNDEFINED-ERROR ) ; not found!
```

```
;; A Result is one of:
;; - Number
;; …
;; - UNDEFINED-ERROR
```

An “error” is a valid program “Result”!

… for now, just represent with special Result value

NOTE: we don’t want Racket exception because this is a “CS450 Lang error” … Racket program runs fine!

env-lookup

```
;; env-lookup: Env Var -> Result
```

```
(define (env-lookup env target-x)
  (cond
   [(empty? env) … ]
   [else
    (match-let
        ([`((,x ,res) . rest-env) env])
      … x … res … (env-lookup rest-env … ) … ]))
```

TEMPLATE!

env-lookup: empty (error) case

```
;; env-lookup: Env Var -> Result
(define (env-lookup env target-x)
  (cond
   [(empty? env) UNDEFINED-ERROR]
   [else
    … ]))
```

env-lookup: non-empty case

```
;; env-lookup: Env Var -> Result
(define (env-lookup env target-x)
  (cond
   [(empty? env) UNDEFINED-ERROR]
   [else
    (match-let
        ([`((,x ,res) . rest-env) env])
     … x … res … (env-lookup rest-env … ) … ]))
```

Extract the pieces

env-lookup: non-empty case

```
;; env-lookup: Env Var -> Result
(define (env-lookup env target-x)
  (cond
   [(empty? env) UNDEFINED-ERROR]
   [else
    (match-let
        ([`((,x ,res) . rest-env) env])
      (if (var=? x target-x)
          res
         … (env-lookup rest-env … ) … ]))
```

Found target-x

env-lookup: non-empty case

```
;; env-lookup: Env Var -> Result
(define (env-lookup env target-x)
  (cond
   [(empty? env) UNDEFINED-ERROR]
   [else
    (match-let
        ([`((,x ,res) . rest-env) env])
      (if (var=? x target-x)
          res
          (env-lookup rest-env target-x)))]))
```

Else, recursive call with remaining env

run, with an Environment accumulator

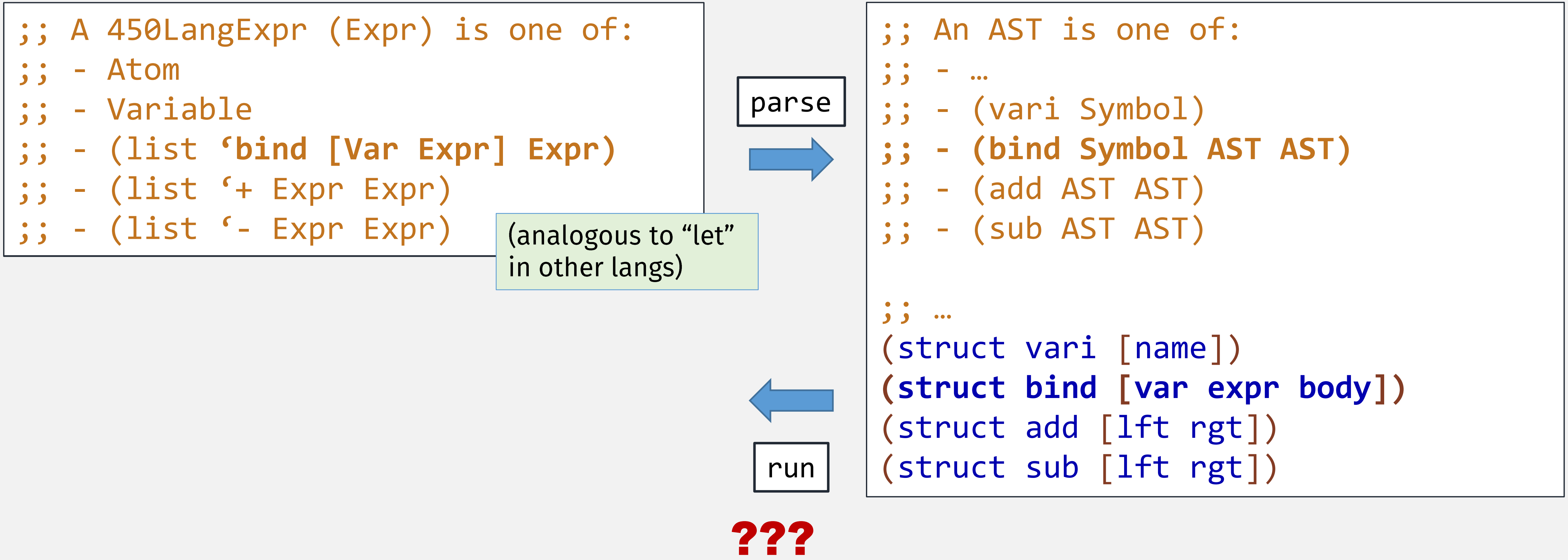
```
;; run: AST -> Result
(define (run p)
  ;; accumulator env : Environment
  ;; invariant: contains in-scope var + results
  (define (run/env p env)
    (match p
     [(num n) n]
     [(add x y) (450+ (run/env x) (run/env y))]))
 (run/env p  ???  ))
```

run, with an Environment accumulator

TODO:
- When are variables "added" to environment
- What is initial environment?

```
;; run: AST -> Result
(define (run p)
  ;; accumulator env : Environment
  ;; invariant: contains in-scope var + results
  (define (run/env p env)
    (match p
      …
      [(vari x) (env-lookup env x)]
      [(bind ??? body) … (env-add env x (r???env e env)) …]
      …   ))
 (run/env p  ???  ))
```

Programs that Add Variables to Environment



```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (list ‘+ Expr Expr)
;; - (list ‘- Expr Expr)
```

(analogous to “let” in other langs)

```
;; An AST is one of:
;; - …
;; - (vari Symbol)
;; - (bind Symbol AST AST)
;; - (add AST AST)
;; - (sub AST AST)

;; …
(struct vari [name])
(struct bind [var expr body])
(struct add [lft rgt])
(struct sub [lft rgt])
```

???

Bind scoping examples

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (list ‘+ Expr Expr)
;; - (list ‘- Expr Expr)
```

This is called “**lexical**” or “**static**” scoping

Generally accepted to be “**best choice**”
for programming language design
(it’s determined only by program syntax)

We will use this for “CS450 Lang”

```
(check-equal?
  (eval450 ‘(bind [x 10] x))
  10 ) ; no shadow
```

Variable reference

```
(check-equal?
  (eval450 ‘(bind [x 10] (bind [x 20] x)))
  20 ) ; shadow
```

```
(check-equal?
  (eval450
    ‘(bind [x 10]
       (+ (bind [x 20]
             x)
          x))) ; 2nd x out of scope here
  30 )
```

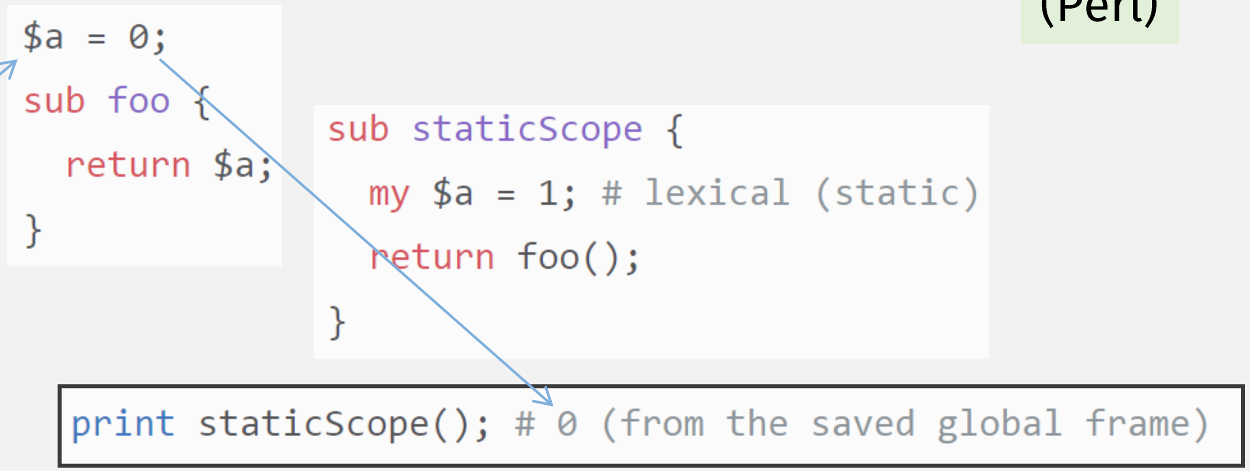
Variable references

```
(check-equal?
  (eval450
   ‘(bind [x 10]
     (bind [x (+ x 20)] ; x = 10 here
       x))) ; x = 30 here
   30 )
```

Different Kinds of Scope

(Perl)

- **Lexical (Static)** Scope
  - Variable value determined by **syntactic** code location

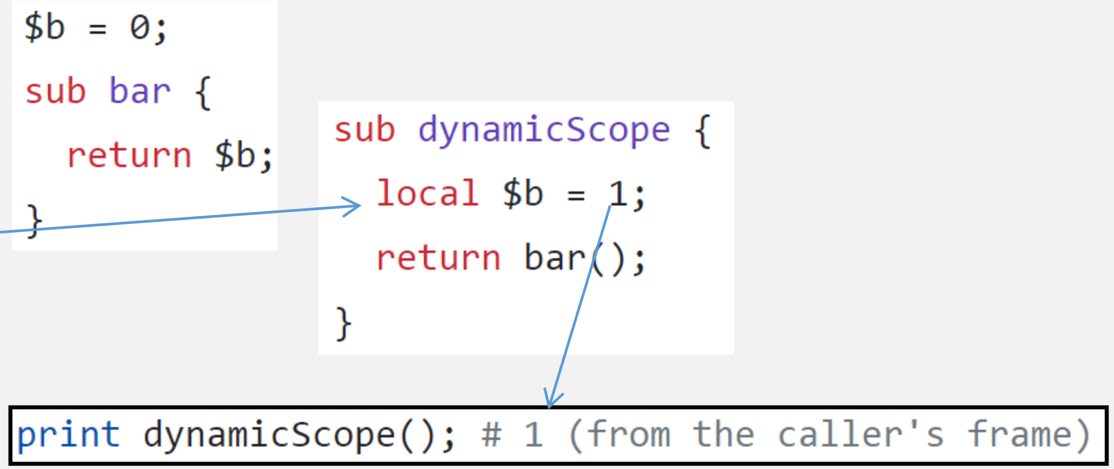


```
$a = 0;
sub foo {
  return $a;
}
```

```
sub staticScope {
  my $a = 1; # lexical (static)
  return foo();
}
```

```
print staticScope(); # 0 (from the saved global frame)
```

- **Dynamic** Scope
  - Variable value determined by **runtime** code location
  - Discouraged: **violates "separation of concerns" principal**



```
$b = 0;
sub bar {
  return $b;
}
```

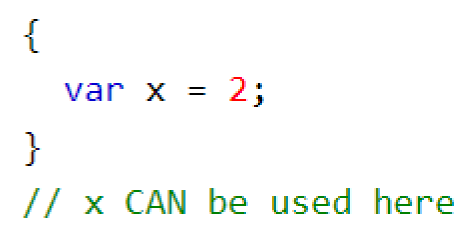
```
sub dynamicScope {
  local $b = 1;
  return bar();
}
```

```
print dynamicScope(); # 1 (from the caller's frame)
```

(eval450-hook) needed "dynamic scope"

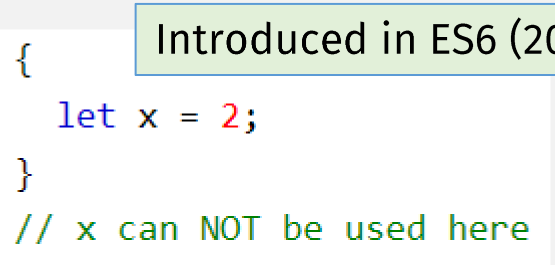
Other Kinds of Scope

- JS “function scope”
  - `var` declarations
    - follow lexical scope inside functions
    - but <u>not</u> other blocks! (weird?)



```
{
  var x = 2;
}
// x CAN be used here
```

  - `let` declarations
    - follow lexical scope inside functions
    - and <u>all</u> other blocks!



```
{
  let x = 2;
}
// x can NOT be used here
```

Introduced in ES6 (2015) to fix var weirdness

- Global scope
  - Variables in-scope everywhere
  - Added to “initial environment” before program runs

run, with an Environment accumulator

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
;; run: AST -> Result
(define (run p)
  ;; accumulator env : Environment
  ;; invariant: contains in-scope var + results
  (define (run/env p env)
    (match p
      …
     [(vari x) (env-lookup env x)]
     [(bind x e body) … (env-add env x (run/env e env)) …]
      …   ))
 (run/env p  ???  ))
```

Environment has **Results** (not **AST**)

How to convert **AST** to **Result**?

(From template!)

Be careful to get correct "**scoping**"
(x not visible in expression e,
so use unmodified input env)

run, with an Environment accumulator

```
;; run: AST -> Result
(define (run p)
  ;; accumulator env : Environment
  ;; invariant: contains in-scope var + results
  (define (run/env p env)
    (match p
      …
      [(vari x) (env-lookup env x)]
      [(bind x e body) ??? (env-add env x (run/env e env)) …]
      …   ))
 (run/env p  ???  ))
```

run, with an Environment accumulator

```
;; run: AST -> Result
(define (run p)
  ;; accumulator env : Environment
  ;; invariant: contains in-scope var + results
  (define (run/env p env)
    (match p
      …
      [(vari x) (env-lookup env x)]
      [(bind x e body) (run/env body (env-add env x (run/env e env)))]
      …    ))
 (run/env p  ???  ))
```

(From template!)

run body with new env containing **x**

Initial Environment?

TODO:

- ~~When are variables "added" to environment~~
- What is initial environment? `empty` (for now)

```
;; run: AST -> Result
```

```
(define (run p)
 ;; accumulator env : Environment
 ;; invariant: contains in-scope var + results
 (define (run/env p env)
   (match p
      …
     [(vari x) (env-lookup env x)]
     [(bind x e body) (run/env body (env-add env x (run/env e env)))]
      …    ))
 (run/env p  ???   ))
```

```
empty ???
```

(for now)

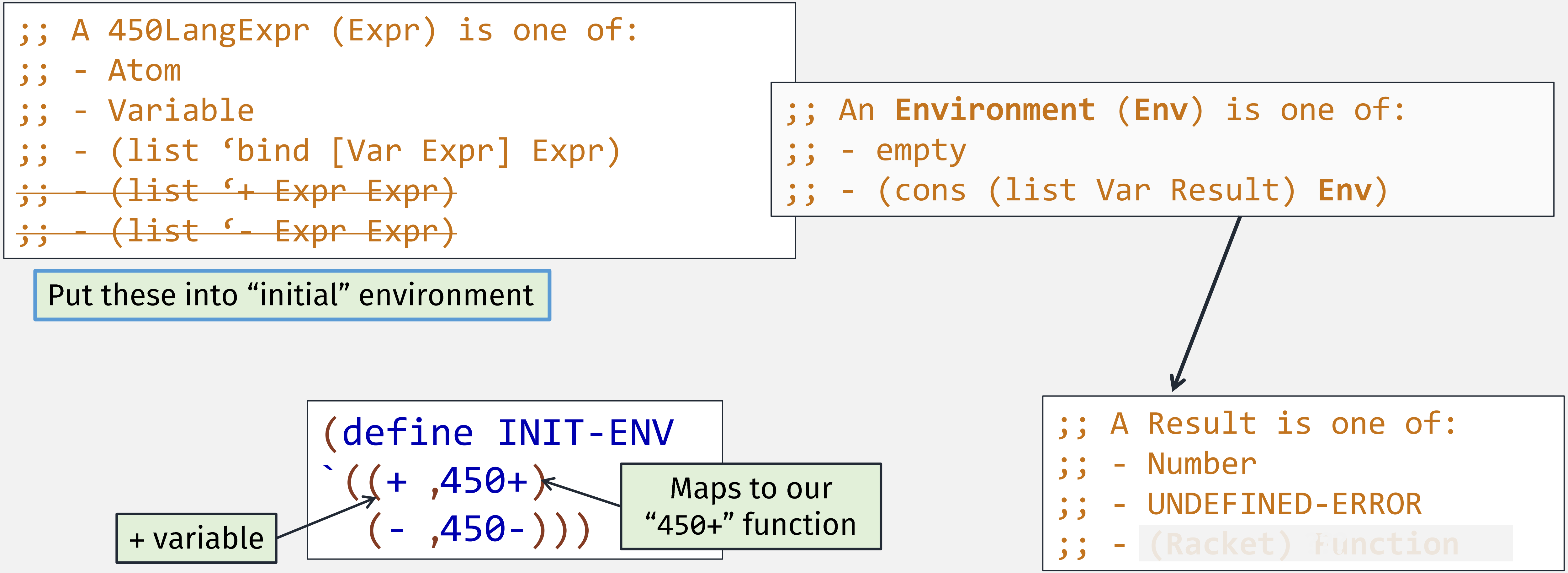
Initial Environment

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (list ‘+ Expr Expr)
;; - (list ‘- Expr Expr)
```

These don’t need to be separate constructs

Put these into “initial” environment

Initial Environment



```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
~~;; - (list ‘+ Expr Expr)~~
~~;; - (list ‘- Expr Expr)~~
```

Put these into “initial” environment

```
;; An Environment (Env) is one of:
;; - empty
;; - (cons (list Var Result) Env)
```

```
;; A Result is one of:
;; - Number
;; - UNDEFINED-ERROR
;; - (Racket) Function
```

```
(define INIT-ENV
`((+ ,450+)
  (- ,450-)))
```

+ variable

Maps to our “450+” function

Initial Environment

How do users call these functions???

```
(define INIT-ENV ‘((+ ,450+) (- ,450-)))
```

```
(define (run p)

  ;; accumulator env : Environment
  (define (run/e p env)
    (match p
      …
     [(vari x) (lookup env x)]
     [(bind x e body) (run/e body (env-add env x (run/e e env)))]
      … ))
 (run/e p INIT-ENV    ))
```

Function Application in CS450 Lang

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (list ‘fncall Expr . List<Expr>)
```

function

arguments

“rest” arg

Specifies arbitrary number of args

Function Application in CS450 Lang: Examples

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (list ‘fncall Expr . List<Expr>)
```

function

arguments

```
(fncall + 1 2)
```

Programmers shouldn’t need to write the explicit “fncall”

Function Application in CS450 Lang: Examples

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (cons Expr List<Expr>)
```

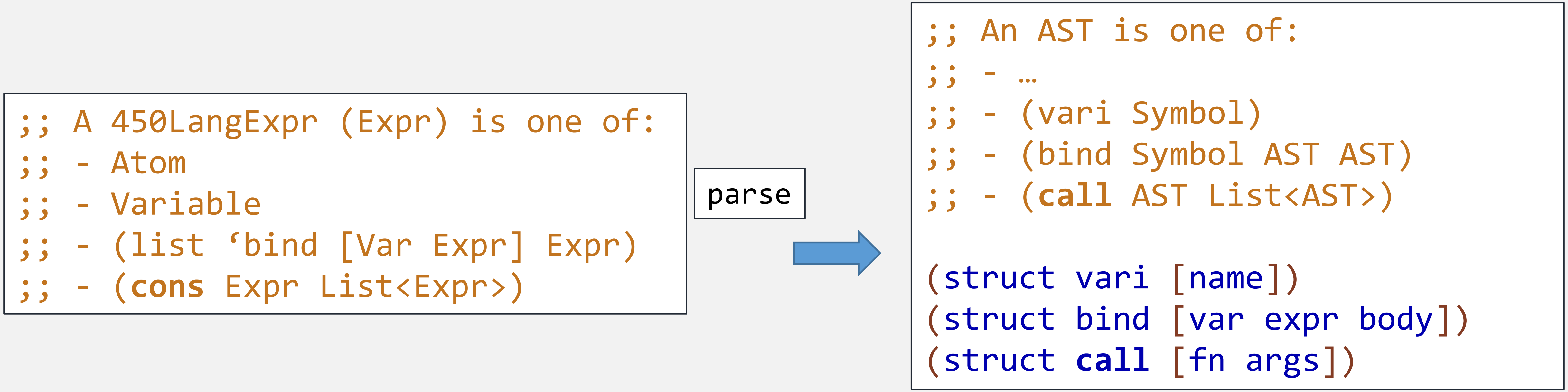
```
(+ 1 2)
```

Function call case (must be last, why?)

No longer need “rest” arg (why?)

Must be careful when parsing this (HW 11!)

Function Application in CS450 Lang



```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (cons Expr List<Expr>)
```

parse

```
;; An AST is one of:
;; - …
;; - (vari Symbol)
;; - (bind Symbol AST AST)
;; - (call AST List<AST>)

(struct vari [name])
(struct bind [var expr body])
(struct call [fn args])
```

“Running” Function Calls

TEMPLATE: extract pieces of compound data

```
;; An AST is one of:
;; - …
;; - (vari Symbol)
;; - (bind Symbol AST AST)
;; - (call AST List<AST>)

(struct vari [name])
(struct bind [var expr body])
(struct call [fn args])
```

```
(define (run p)


  (define (run/e p env)
    (match p
        …
     [(call fn args) (apply
                       (run/e fn env)
                       (map (curryr run/e env) args))]

        …
     ))
 (run/e p INIT-ENV))
```

“Running” Function Calls

```
;; An AST is one of:
;; - …
;; - (vari Symbol)
;; - (bind Symbol AST AST)
;; - (call AST List<AST>)
```

```
(define (run p)


  (define (run/e p env)
    (match p
        …
     [(call fn args) (apply
                        (run/e fn env)
                        (map (curry??? run/e env) args))]

        …
     ))
 (run/e p INIT-ENV))
```

TEMPLATE: recursive calls

“run” args before calling function – “call by value”

“Running” Function Calls

How do we actually run the function?

```
;; A Result is one of:
;; - Number
;; - UNDEFINED-ERROR
;; - (Racket) Function
```

```
(define (run p)



  (define (run/e p env)
    (match p
         …
     [(call fn args) (apply ???
                         (run/e fn env)
                         (map (curryr run/e env) args))]

         …
     ))
 (run/e p INIT-ENV))
```

(this only “works” for now)

Function Application in CS450 Lang

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (cons Expr List<Expr>)
```

Function call case (must be last)

This doesn’t let users define their own functions!

Next Feature: **Lambdas?**

- Repo: **cs450f24/in-class-11-18**
- File: **bind-examples-**<*your last name*>**.rkt**

In-class Coding 11/18: bind + “call” examples

```
;; A 450LangExpr (Expr) is one of:
;; - Atom
;; - Variable
;; - (list ‘bind [Var Expr] Expr)
;; - (cons Expr List<Expr>)
```

Come up with some of your own!

```
(check-equal?
  (eval450 ‘(bind [x 10] x))
  10 ) ; no shadow
```

```
(check-equal?
  (eval450 ‘(bind [x 10] (bind [x 20] x))
  20 ) ; shadow
```

```
(check-equal?
  (eval450
    ‘(bind [x 10]
       (+ (bind [x 20]
            x)
          x)) ; 2nd x outof scope here
  30 )
```

```
(check-equal?
  (eval450
   ‘(bind [x 10]
      (bind [x (+ x 20)] ; x = 10 here
        x))) ; x = 30 here
   30 )
```