Part I

Lexical Addresses and Compilation

Identifier Address

Suppose that

```
{fun {x} {+ x y}}
```

appears in a program...

If the body is eventually evaluated:

```
         ...
{+ x y}
```

where will **x** be in the substitution?

Answer: always at the beginning:

```
x = ...    ...
```

Identifier Address

Suppose that

```
{with {y 1} {+ x y}}
```

appears in a program...

If the body is eventually evaluated:

```
...
{+ x y}
```

where will **y** be in the substitution?

Answer: always at the beginning:

```
y = 1   ...
```

Identifier Address

Suppose that

```
{with {y 1}
  {fun {x} {+ x y}}}
```

appears in a program...

If the body is eventually evaluated:

```
       ...
{+ x y}
```

where will **y** be in the substitution?

Answer: always second:

```
x = ...   y = 1   ...
```

Identifier Address

Suppose that

```
{with {y 1}
  {{fun {x} {- {+ x y} 17}} 88}}
```

appears in a program...

If the body is eventually evaluated:

```
...
{+ x y}
```

where will **x** and **y** be in the substitution?

Answer: always first and second:

```
x = ...   y = 1   ...
```

Identifier Address

Suppose that

```
{with {y 1}
  {{fun {w} {with {z 9}
              {fun {x} {+ x y}}}}}}
```

appears in a program...

If the body is eventually evaluated:

```
       ...
{+ x y}
```

where will **`x`** and **`y`** be in the substitution?

Answer: always first and fourth:

```
x = ...   z = 9   w = ...   y = 1   ...
```

Identifier Address

Suppose that

```
{with {y {with {r 8} {f {fun {x} r}}}}
  {{fun {w} {with {z 9}
                {fun {x} {+ x y}}}}}}
```

appears in a program...

If the body is eventually evaluated:

```
                ...
{+ x y}
```

where will **x** and **y** be in the substitution?

Answer: always first and fourth:

```
x = ...    z = 9    w = ...    y = ...    ...
```

Lexical Scope

Our language is ***lexically scoped***:

- For any expression, we can tell which identifiers will have substititions at run time
- The order of the substitutions is also predictable

(The value for each substitution is not necessarily predictable)

Compiling FAE

A ***compiler*** can transform **`FAE`** expressions to expression without identifiers – only lexical addresses

```
; compile : FAE ... -> CFAE
```

```
(define-type FAE
  [num (n number?)]
  [add (lhs FAE?)
       (rhs FAE?)]
  [sub (lhs FAE?)
       (rhs FAE?)]
  [id (name symbol?)]
  [fun (param symbol?)
       (body FAE?)]
  [app (fun-expr FAE?)
       (arg-expr FAE?)])
```

```
(define-type CFAE
  [cnum (n number?)]
  [cadd (lhs CFAE?)
        (rhs CFAE?)]
  [csub (lhs CFAE?)
        (rhs CFAE?)]
  [cat (pos number?)]
  [cfun (body CFAE?)]
  [capp (fun-expr CFAE?)
        (arg-expr CFAE?)])
```

Compile Examples

`(compile 1 ...)` ⇒ `1`

`(compile {+ 1 2} ...)` ⇒ `{+ 1 2}`

`(compile x ...)` ⇒ *compile: free identifier*

`(compile {fun {x} x} ...)` ⇒ `{fun {at 0}}`

`(compile {fun {y} {fun {x} {+ x y}}} ...)`
⇒ `{fun {fun {+ {at 0} {at 1}}}}`

`(compile {{fun {x} x} 10} ...)`
⇒ `{{fun {at 0}} 10}`

Implementing the Compiler

```
; compile : FAE CSubs -> CFAE
(define (compile a-fae cs)
  (type-case FAE a-fae
    [num (n) (cnum n)]
    [add (l r) (cadd (compile l cs)
                     (compile r cs))]
    [sub (l r) (csub (compile l cs)
                     (compile r cs))]
    [id (name) (cat (locate name cs))]
    [fun (param body-expr)
         (cfun (compile body-expr
                        (aCSub param cs)))]
    [app (fun-expr arg-expr)
         (capp (compile fun-expr cs)
               (compile arg-expr cs))]))
```

Compile-Time Substitution

Mimics run-time substitutions, but without values:

```
(define-type CSubs
  [mtCSub]
  [aCSub (name symbol?)
         (rest CSubs?)])

; locate : symbol CSubs -> number
(define (locate name cs)
  (type-case CSubs cs
    [mtCSub ()
            (error 'compile "free identifier")]
    [aCSub (sub-name rest)
           (if (symbol=? name sub-name)
               0
               (+ 1 (locate name rest)))]))
```

CFAE Values

Values are still numbers or closures, but a closure doesn't need a parameter name:

```
(define-type CFAE-Value
  [cnumV (n number?)]
  [cclosureV (body CFAE?)
             (subs list?)])
```

CFAE Interpreter

Almost the same as **FAE `interp`**:

```
; cinterp : CFAE list-of-CFAE-Value -> CFAE-Value
(define (cinterp a-cfae subs)
  (type-case CFAE a-cfae
    [cnum (n) (cnumV n)]
    [cadd (l r) (cnum+ (cinterp l subs) (cinterp r subs))]
    [csub (l r) (cnum- (cinterp l subs) (cinterp r subs))]
    [cat (pos) (list-ref subs pos)]
    [cfun (body-expr)
          (cclosureV body-expr subs)]
    [capp (fun-expr arg-expr)
         (local [(define fun-val
                   (cinterp fun-expr subs))
                 (define arg-val
                   (cinterp arg-expr subs))]
          (cinterp (cclosureV-body fun-val)
                   (cons arg-val
                         (cclosureV-subs fun-val))))]))
```

CFAE Versus FAE Interpretation

On my machine,

```
(cinterp
 {{{{{fun {fun {fun {fun {at 3}}}}} 10} 11} 12} 13}
 empty)
```

is 30% faster than

```
(interp
 {{{{{fun {x} {fun {y} {fun {z} {fun {w} x}}}} 10} 11} 12} 13}
 (mtSub))
```

Note: using built-in `list-ref` simulates machine array indexing, but don't take the numbers too seriously

Part II

Dynamic Scope

Recursion

What if we want to write a recursive function?

```
{with {f {fun {x} {f {+ x 1}}}}
  {f 0}}
```

This doesn't work, because `f` is not bound in the right-hand side of the `with` binding

But by the time that `f` is called, `f` is available...

Dynamic Scope

```
{with {f {fun {x} {f {+ x 1}}}}
  {f 0}}
```

`f = {fun {x} {f {+ x 1}}}`

⇒ `{f 0}`

Lexical scope:

`x = 0`

⇒ `{f {+ x 1}}`

Dynamic scope:

`x = 0    f = {fun {x} {f {+ x 1}}}`

⇒ `{f {+ x 1}}`

Implementing Dynamic Scope

```
; dinterp : FAE SubCache -> FAE-Value
(define (dinterp a-fae sc)
  (type-case FAE a-fae
    [num (n) (numV n)]
    [add (l r) (num+ (dinterp l sc) (dinterp r sc))]
    [sub (l r) (num- (dinterp l sc) (dinterp r sc))]
    [id (name) (lookup name sc)]
    [fun (param body-expr)
         (closureV param body-expr (mtSub))]
    [app (fun-expr arg-expr)
         (local [(define fun-val
                   (dinterp fun-expr sc))
                 (define arg-val
                   (dinterp arg-expr sc))]
           (dinterp (closureV-body fun-val)
                    (aSub (closureV-param fun-val)
                          arg-val
                          sc))))]))
```

Benefits of Dynamic Scope

Dynamic scope looks like a good idea:

- *Seems* to make recursion easier
- Implementation *seems* simple:
  - No closures; change to our interpreter is trivial
  - There's only one binding for any given identifier at any given time
- Supports optional arguments:

```
{with {x 0}
  {with {f {fun {y} {+ x y}}}
    {+ {f 1} ; use default x
       {with {x 3} ; change x to 3
         {f 2}}}}}
```

Drawbacks of Dynamic Scope

There are serious problems:

- **`lambda`** doesn't work right

```
(define (num-op op op-name)
  (lambda (x y)
    (numV (op (numV-n x) (numV-n y)))))
```

- It's easy to accidentally depend on dynamic bindings
- It's easy to accidentally override a dynamic binding

The last two are unacceptable for large systems

⇒ make your language statically scoped

A Little Dynamic Scope Goes a Long Way

Sometimes, the programmer really needs dynamic scope:

```
(define (notify user msg)
  ; Should go to the current output stream,
  ; whatever that is for the current process:
  (printf "Msg from ~a: ~a\n" user msg))
```

Static scope should be the implicit default, but supporting explicit dynamic scope is a good idea:

- In Common LISP, variables can be designated as dynamic
- In PLT and other Schemes, special forms can be used to define and set dynamic bindings:

```
(define x (make-parameter 0))
(define (f y)
  (+ y (x)))
(+ (f 1) (parameterize ([x 3])
           (f 2)))
```

HW 4

- Change **`fun`** and **`app`** to allow multiple arguments
- Add support for records
- **Extra credit:** Add support for dynamic bindings