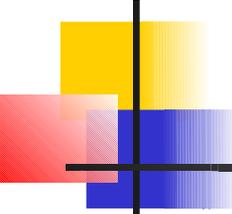


Clever Programming With Functions

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Using Functions to Represent Objects

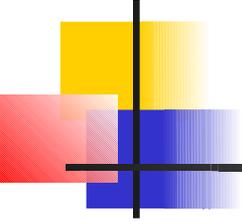
- How can we represent a pair in Scheme so that the only operations that code can perform on pairs are:

```
(make-pair x y)
(pair-first p)
(pair-second p)
(pair-equal? p1 p2)
```

- What if we represent a pair as a list? As a struct? Structs are not as robust as you might think. In the advanced language level try:

```
(define-struct Pair (first second))
(define p (make-Pair 1 2))
(set-Pair-first! P 17)
```

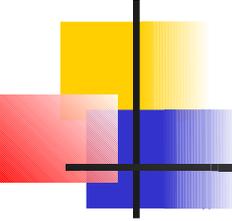
p



Objects as closures

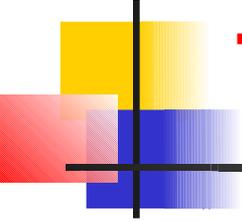
```
(define (make-pair x y)
  (lambda (msg)
    (cond [(equal? msg 'first) (lambda () x)]
          [(equal? msg 'second) (lambda () y)]
          [(equal? msg 'equal)
           (lambda (p)
             (and (equal? (pair-first p) x)
                  (equal? (pair-second p) y)))])))
(define (pair-first p) ((p 'first)))
(define (pair-second p) ((p 'second)))
(define (pair-equal? p1 p2) ((p1 'equal) p2))
```

This representation trick is very important. It shows how closures (functions with free variables treated as first-class data values) can be used to represent abstract (black-box) data types.



Useful Functionals

- What is a *functional*? A function that takes a function as a argument and often returns a function. The differential and integral operators in calculus are functionals.
- Important functionals in functional programming:
`map filter foldr foldl curry`



The Idea Behind `curry`

- Every function of the form

$$A \times B \rightarrow C$$

can be converted to a function of type

$$A \rightarrow (B \rightarrow C)$$

which is often more convenient.

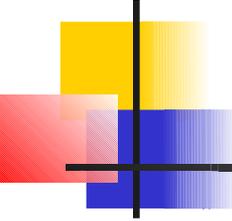
- In set theory, here is an isomorphism between

$$A \times B \rightarrow C$$

and

$$A \rightarrow B \rightarrow C$$

- This correspondence *roughly* holds for programming language types.



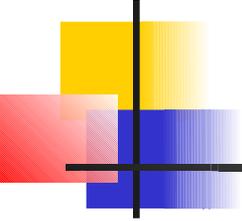
A Simple Example

`map : A B -> C`

`map : (X -> Y) (list-of X) -> (list-of Y)`

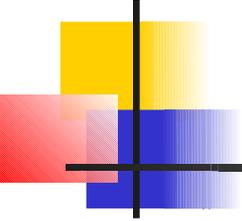
`map' : A -> (B -> C)`

`map' : (X -> Y) -> (list-of X) -> (list-of Y)`



Standard Map

```
(define map
  (lambda (f l)
    (cond
      [(empty? l) empty]
      [else
       (cons (f (first l))
              (map f (rest l))) ]))
```



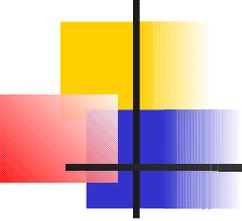
Curried Map

- A definition in terms of `map`

```
(define (map' f)
  (lambda (l) (map f l)))
```

- When written from scratch, it looks almost exactly like `map`:

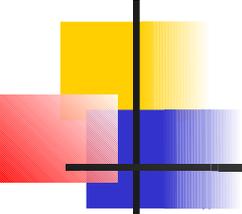
```
(define map'
  (lambda (f)
    (lambda (l)
      (cond
        [(empty? l) empty]
        [else (cons (f (first l))
                     (map f (rest l)))])))
```



Can We Define a Functional that Curries?

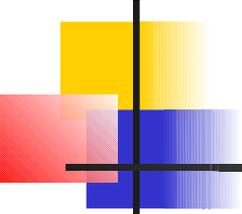
Unfortunately, we need a separate curry function for each function arity ≥ 2 .

```
(define (curry f)
  (lambda (x)
    (lambda (y) (f x y))))
```



Uncurry

- Question: See if you can write
$$\text{uncurry} : (A \rightarrow (B \rightarrow C)) \rightarrow (A \ B \rightarrow C)$$
- Note the equational properties:
$$\text{curry} (\text{uncurry } f) = f$$
$$\text{uncurry} (\text{curry } f) = f$$
- These are laws in mathematics, but the first fails in programming languages even when f is restricted to a value. It doesn't hold in either CBN or CBV. Why?
The left-hand side never throws an exception or diverges on the first application.
- Both equations fail if f can be an expression rather than a value of the appropriate type. Why? The evaluation of the left hand side never diverges or generates an exception.
- Yet these equations are widely taught by PL experts as if PL domain theory was set theory. They are NOT identities for PL code!



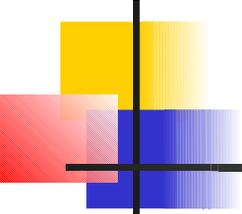
The Crux of The Difference

- Why don't functional languages obey standard laws from set theory?
- *Eta*-conversion fails in the PL world which admits divergent definitions.
- *Eta*-conversion is often added as an axiom to the λ -calculus. It does not disturb the major properties.
- *Eta*-conversion asserts:
$$\lambda x. Ex = E \quad (\text{where } x \text{ does not occur free in } E)$$
- It fails even when the type of E is restricted to a unary function type.

Bonus Material

Another Important Functional: Y

- lambda-notation (as in Scheme) indirectly supports recursion. How? A clever construction based on sophisticated mathematics (lambda-calculus).
- Short story: solutions to recursion equations are "fixed points". Given the equation
$$f(x) = E_f \text{ (which is equivalent to } f = \lambda x. E_f)$$
what is the least solution f^* ? Under proper conditions,
$$f^* = \mathbf{lub} F^i(\perp)$$
where $F(f) = \lambda x. E_f$) and \perp is the least-defined function (i.e., the function denoted by Ω). Y is defined by $Y(F) = f^*$ where (f^* is least solution of $F(f^*) = f^*$).



Defining Y

- λ -calculus programming trick: use a variation on

$$\Omega = (\text{self self})^k [(\lambda x. f(x x)) (\lambda x. f(x x))] = \dots (\text{self self})$$

$$(\lambda x. f(x x)) (\lambda x. f(x x)) = f[(\lambda x. f(x x)) (\lambda x. f(x x))]$$

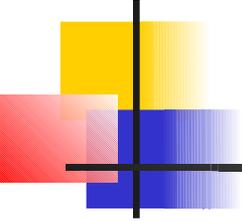
$$= f^2[(\lambda x. f(x x)) (\lambda x. f(x x))] = \dots$$

$$= f^k[(\lambda x. f(x x)) (\lambda x. f(x x))] = \dots$$

- In CBN languages

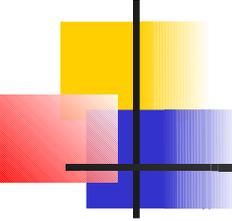
$$Y = \lambda f . (\lambda x. f(x x)) (\lambda x. f(x x))$$

- CBV is slightly harder and messier because YF does not terminate. Trick: convert the term $(\lambda x. f(x x))$ to $(\lambda x. [\lambda y. f(x x)]y)$ (eta-conversion of the diverging term).
- Default for λ -calculus is CBN. Default for programming languages is CBV.



Bonus Material: Other Powerful Functionals: S,K

- Every closed λ -expression can be written without **any** variables given the three primitive functionals **S**, **K**, **I** where
 - **S** = $\lambda x. \lambda y. \lambda z. (xz)(yz)$
 - **K** = $\lambda x. \lambda y. X$
 - **I** = $\lambda x. x$
- In fact, you only need two because
 - **I** = **S(KK)**
- Functionals defined by closed λ terms (and nothing else) are called **combinators**. **Y** (in all its varieties) is a combinator.



For Next Class

- Homework due Friday
- Review of Scheme material in lecture on Wednesday and Friday.
- Reading:
 - Review for coming exam which will be distributed on Friday.