Today we will...

- Introduce a functional pattern monads
- Introduce state monads
- Introduce stack machines
Functional pattern:Mutable state
Revisiting our reduction rules

\[ \triangleright_E \ u \ \downarrow_E \ u \ \triangleright_H \]

\[ \triangleright_{H_1} \ e_f \ \downarrow_E \ (E_f, \lambda x.t_b) \ \triangleright_{H_2} \ e_a \ \downarrow_E \ v_a \ \triangleright_{H_3} \ E_b \leftarrow E_f + [x := v_a] \ \triangleright_{H_4} \ t_b \ \downarrow_E \ v_b \ \triangleright_{H_5} \]

\[ \triangleright_{H_1} (e_f \ e_a) \ \downarrow_E \ v_b \ \triangleright_{H_5} \]

Effectful computation can be divided into three categories:

- Side-effect free computation in **blue**
- Computation that directly produces side effect in **red**
- Computation that indirectly produces some side-effect in **black**

We are \( \triangleright \) chaining \( \triangleright \) effectful \( \triangleright \) computations \( \triangleright \), that is the variables declared on the left-hand side of \( \triangleright \) should be accessible in the right-hand side.
Refactoring memory-based operations

```
;; e1 ⊣E v1
(define v1+mem1 (d:eval-exp mem env e1))
(define mem1 (eff-state v1+mem1))
(define v1 (eff-result v1+mem1))
;; E' ← E + [x := v1]
(define env2+mem2 (environ-push mem1 env y v1))
(define env2 (eff-result env2+mem2))
(define mem2 (eff-state env2+mem2))
;; e2 ⊣E' v2
(define v2+mem3 (d:eval-exp mem2 env2 e2))
(define mem3 (eff-state v2+mem3))
(define v2 (eff-result v2+mem3))
```

The memory needs to be passed along from one function call to the next. How can we refactor this code so that some function does that for us?
Refactoring evaluation of application

At each step we separate the result from the state. Our goal is to **abstract** the memory threading, that is to refactor away this mechanic unpacking of the side effect structure.

```scheme
;; e1 \[\!\! E \!\!\! v1
(define* v1 (d:eval-exp* env e1))
;; E' \[\!\! E + [x := v1]
(define* env2 (environ-push* env y v1))
;; e2 \[\!\! E' \!\!\! v2
(define* v2 (d:eval-exp* env2 e2))
```
Abstracting the state

Ideal pseudo code

In today's class, we introduce an abstraction that allows us to achieve something similar to the pseudo-code below. We highlight in yellow effectful definitions and operations.

```
;; e1 \(\downarrow E\) v1
(define* v1 (d:eval-exp* env e1))
;; \(E' \leftarrow E + \left\{x := v1\right\}\)
(define* env2 (environ-push* env y v1))
;; e2 \(\downarrow E'\) v2
(define* v2 (d:eval-exp* env2 e2))
```
Roadmap: abstracting effectful computation

Combining:

- **Effectful operations**: `s:eval-exp` and `environ-push`, with
- **Effectful variable declaration**: `v1`, `env2`, and `v2`

```scheme
;; e1 ⇓E v1
(define* v1 (d:eval-exp* env e1))
;; E' ← E + [x := v1]
(define* env2 (environ-push* env y v1))
;; e2 ⇓E' v2
(define* v2 (d:eval-exp* env2 e2))
```

```
e_1 \downarrow_E v_1 \triangleright E' \leftarrow E + [y := v] \triangleright e_2 \downarrow_{E'} v_2
```
A proxy example

Arithmetic on the heap
Example

Consider a heap of integers. We allocate two integers and then a third integer that holds the sum of the first two.

```
(define (prog1 h1)
  ;; allocate x with 1
  (define eff-x (heap-alloc h1 1))
  (define x (eff-result eff-x))
  (define h2 (eff-state eff-x))

  ;; allocate y with 2
  (define eff-y (heap-alloc h2 2))
  (define y (eff-result eff-y))
  (define h3 (eff-state eff-y))

  ;; allocate z with (+ x y)
  (heap-alloc h3 (+ (heap-get h3 y) (heap-get h3 x))))

(define (run-state h op) (eff-state (op h)))
(define H (heap (hash (handle 0) 1 (handle 1) 2 (handle 2) 3)))
(check-equal? (run-state empty-heap prog1) H)
```
Effectful operations

- An **effectful operation** takes a state and returns an effect `eff` that pairs some state with some result. An effectful operation is parameterized by the state type and by the result type.
- Below we define two effectful operations where the state is a heap.

### Alloc

```
(define (num x)
  (lambda (h)
    (heap-alloc h x)))
```

### Add

```
(define (add x y)
  (lambda (h)
    (heap-alloc h (+ (heap-get h y) (heap-get h x)))))
```

---

**Did you know?**

- The state (heap) is a parameter, so that we can combine effectful operations.
- Functions `num` and `add` each returns an effectful operation.
Sequencing effectful operations

Example

```
(define (prog2 h1)
  ;; allocate x with 1
  (define eff-x ((num 1) h1))
  (define x (eff-result eff-x))
  (define h2 (eff-state eff-x))

  ;; allocate x with 2
  (define eff-y ((num 2) h2))
  (define y (eff-result eff-y))
  (define h3 (eff-state eff-y))

  ;; allocate y with (+ x y)
  ((add x y) h3))
```

The bind operator

```
(define (bind o1 o2)
  (lambda (h1)
    (define eff-r (o1 h1))
    (define r (eff-result eff-r))
    (define h2 (eff-state eff-r))
    ((o2 r) h2))
```

We highlight in yellow an example of redundant code. Function bind abstracts away the redundant code.
Abstracting with bind

Before

```
(define (prog2 h1)
  ;; allocate x with 1
  (define eff-x ((num 1) h1))
  (define x (eff-result eff-x))
  (define h2 (eff-state eff-x))
  ;; allocate x with 2
  (define eff-y ((num 2) h2))
  (define y (eff-result eff-y))
  (define h3 (eff-state eff-y))
  ;; allocate y with (+ x y)
  ((add x y) h3))
```

After

```
(define prog3
  ;; allocate x with 1
  (bind (num 1)
    (lambda (x)
      ;; allocate x with 2
      (bind (num 2)
        (lambda (y)
          ;; allocate y with (+ x y)
          (add x y))))))
```

Using the bind operator we remove redundant code. You can think of bind as a variable declaration, akin to an effectful define.
Stack machines

The state does not need to be a heap
Stack machines

- Uses a stack of number to represent memory (rather than registers)
- Variable-free code
- Very compact object code
- Examples of (virtual) stack machines: OpenJDK JVM, CPython interpreter

```python
def mult():
    x = pop
    y = pop
    push (x * y)

def prog():
    push(2)
    push(5)
    mult() # 2 * 5 = 10
    push(2)
    mult() # 10 * 2 = 20
```
A stack-based evaluator

Operations

- push(n) \rightarrow (\text{void})
- pop() \rightarrow \text{number}

State
A stack-based evaluator

Operations

- push(n) → (void)
- pop() → number

State

- a list of numbers
Implementing pop

(define (pop)
Implementing pop

```
(define (pop)
  (lambda (stack)
    (eff (rest stack) (first stack))))
```
Implementing push

\[
\text{(define } \text{push n)}
\]
Implementing push

```
(define (push n)
  (lambda (stack)
    (eff (cons n stack) (void)))
)
Implementing `mult`

def mult():
    x = pop
    y = pop
    push (x * y)
Defining function `mult()`:

```python
def mult():
    x = pop
    y = pop
    push (x * y)
```


Callable definition in Lambda Calculus:

```lambda
(define (mult)
    (bind (pop)
        (lambda (x)
            (bind (pop)
                (lambda (y)
                    (push (* x y)))))))
```
Implementing prog

Pseudo Code

```python
def prog():
    push(2)
    push(5)
    mult()  # 2 * 5 = 10
    push(2)
    mult()  # 10 * 2 = 20
```
Implementing prog

Pseudo Code

```python
def prog():
    push(2)
    push(5)
    mult()  # 2 * 5 = 10
    push(2)
    mult()  # 10 * 2 = 20
```

In Racket

```racket
(define prog4
  (bind (push 2)
    (lambda (x1)
      (bind (push 5)
        (lambda (x2)
          (bind (mult)
            (lambda (x3)
              (bind (push 2)
                (lambda (x4)
                  (mult)))))))))))

(check-equal? (run-state (list) prog4) (list 20))
```

Unfortunately, the code appears very nested if we indent it as we usually do. Can we do better?
Sequencing effectful operators
Sequencing effectful operators

Solution

(define (seq2 op1 op2)
  (bind op1 (lambda (x) op2)))

(define (seq op . ops)
  (cond [(empty? ops) op]
        [else (seq2 op (apply seq ops))])))

Revisit prog4
Sequencing effectful operators

Solution

```
(define (seq2 op1 op2)
  (bind op1 (lambda (x) op2)))

(define (seq op . ops)
  (cond [(empty? ops) op]
        [else (seq2 op (apply seq ops))]))
```

Revisit prog4

```
(define prog5
  (seq (push 2)
       (push 5)
       (mult)
       (push 2)
       (mult)))

(check-equal? (run-state (list) prog5) (list 20))
```

Limitations

The `seq` operator is a regular function call, which takes *expressions* as its arguments. This complicates a situation where we might need to create a temporary variable (say to cache a result) in the middle of a `seq`.
Syntactic sugar for stateful operations
Syntactic sugar: the do notation

Macros can be a useful technique to avoid redundant code. In our case, we are using a macro to avoid syntactic verbosity.

```
(define-syntax do
  (syntax-rules (←)
    ; Only one monadic-op, return it
    [(_ mexp) mexp]
    ; A binding operation
    [(_ var ← mexp rest ...) (bind mexp (lambda (var) (do rest ...)))]
    ; No binding operator, just ignore the return value
    [(_ mexp rest ...) (bind mexp (lambda (_) (do rest ...)))]
)
```

You do not need to understand this code today. We will learn about macros in detail in a future lesson.
Syntactic sugar: the do notation

The do notation allows us to make our code less nested. The cost of using macros is that they obfuscate the program’s semantics.

Before

```
(define (mult)
  (bind (pop)
    (lambda (x)
      (bind (pop)
        (lambda (y)
          (push (* x y)))))))
```

After

```
(define (mult)
  (do
    x <- (pop)
    y <- (pop)
    (push (* x y))))
```

Limitations

Similarly to seq, because of how the macro was designed, it takes a sequence of expressions. Monadic interfaces usually introduce an operator `pure` to workaround the issue.
The pure operator

The pure operator simply converts a pure (non-effectful) value into an effectful value, leaving the state unaltered. One useful benefit of this is that it allow us to combine effectful and pure operations in the same interface.

Example

```
(define (pure v)
  (lambda (st)
    (eff st v)))
```

```
(define (mult)
  (do
    x ← (pop)
    y ← (pop)
    z ← (pure (* x y))
    (push z))))
```
Summary: the monad

A monad is a **functional pattern** which can be categorized of two base combinators:

- **Bind**: combines two effectful operations $o_1$ and $o_2$. Operation $o_1$ produces a value that is consumed by operation $o_2$.
- **Pure**: Converts a pure value to a monadic operation, which can then be chained with bind.

In this course, we will learn that the monadic pattern appears in different contexts.
Summary: the state monad

- **Data:** the monadic data is a pair (struct `eff`) that holds the global state and some result.
- **Bind:** combines operation $o_1$ with operation $o_2$; after executing $o_1$, we get a new state and some result that are both fed into operation $o_2$.

To think...

Monadic function application: can we create a function call where all arguments are monadic values? What about a monadic map? And a monadic fold?

```
(define (mult)
  (do
    z ← (mapply * (pop) (pop))
    (push z)))

;; Or, simply: (define (mult) (bind (mapply * (pop) (pop)) push))
```