Recursion, Loops, Stacks, Tail Calls, and Space Safety

Space Complexity

```
(define (sum-to n)
  (cond
    [(zero? n) 0]
    [else (+ n (sum-to (sub1 n)))]))
```

```
(sum-to 10) → (+ 10 (sum-to 9))
            → (+ 10 (+ 9 (sum-to 8)))
            → (+ 10 (+ 9 (+ 8 (sum-to 7))))
```

`(sum-to` n`)` takes $O(n)$ space

Space Complexity

```
(define (sum-to n a)
  (cond
    [(zero? n) a]
    [else (sum-to (sub1 n) (+ n a))]))
```

```
(sum-to 10 0) → (sum-to 9 10)
              → (sum-to 8 19)
              → (sum-to 7 27)
```

`(sum-to` *n* `0)` takes constant space

Actually, it's O(log *n*), but we usually pretend that numbers are represented in constant space

Continuations

In

```
(+ 10 (+ 9 (+ 8 (sum-to 7))))
```

the ***continuation*** of `(sum-to 7)` is

```
(+ 10 (+ 9 (+ 8 •)))
```

That is, the *continuation* of an expression is the work remaining after the expression is evaluated

In particular, the **`sum-to`** with O(n) space complexity creates a continuation of O(n) size

Stacks

A ***stack*** is one way to represent a continuation

`(+ 10 (+ 9 (+ 8 •)))` =

`(+ 10 •)`
`(+ 9 •)`
`(+ 8 •)`

Some language implementations use a fixed-size stack to represent continuations

In a high-level language, there is no good reason for this choice, and it creates problems in practice

Space and Local Bindings

```
(let ([val (make-big-pile-of-data)])
  (+ (f (collapse1 val))
     (g (collapse2 val))))
```

In this example, **`val`** must be retained during the call to **`f`**, because it is needed afterward

Space and Local Bindings

```
(let ([val (make-big-pile-of-data)])
  (+ (f (collapse1 val))
     (g 7)))
```

In this example, **`val`** should *not* be retained during the call to **`f`**, because it is not needed by the time that **`f`** is called

Languages and Space Complexity

Languages sometimes go wrong in these ways:

- Limiting continuation size to ≪ available memory

“stack” usually implies such a limit

- Extending a continuation needlessly

“tail calls” should be handled properly

- Retaining data needlessly

an implementation should be “safe for space”

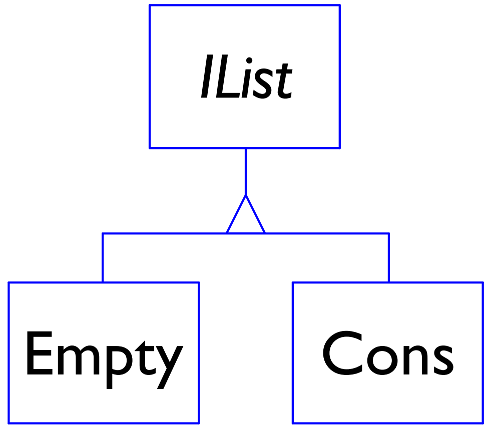
Continuation Sizes Shouldn’t be Limited

Data Drives Design

```
; A list-of-num is either
;   - empty
;   - (cons num list-of-num

(define (sum lon)
  (cond
    [(empty? lon) 0]
    [else (+ (first lon)
             (sum (rest lon)))]))
```

Data Drives Design




```
interface IList {
  int sum();
}
```

```
class Empty implements IList {
  int sum() { return 0; }
}
```

```
class Cons implements IList {
  ...
  int sum() {
    return first + rest.sum();
  }
}
```

Data Drives Design

```
; A num-tree is either
;  - empty
;  - (node num num-tree num-tree)
(struct node (value left right))

(define (sum-tree t)
  (cond
    [(empty? t) 0]
    [else
     (+ (node-value t)
        (sum-tree (node-left t))
        (sum-tree (node-right t)))]))
```

Continuation-Limit Workarounds

With a limited continuation size, programmers must manage continuations themselves:

```
int sumTree(Tree n) {
  int a;
  Stack s = new Stack();
  s.push(n);
  while (!s.isEmpty()) {
    n = s.pop();
    if (!n.isEmpty()) {
      a = a+n.getValue();
      s.push(n.getLeft());
      s.push(n.getRight());
    }
  }
  return a;
}
```

Proper Handling of Tail Calls

Tail Recursion

```
(define (sum-to n a)
  (cond
    [(zero? n) a]
    [else (sum-to (sub1 n) (+ n a))]))
```

The recursive call to `sum-to` is in ***tail position***

There's no more work to do in `sum-to` after the recursive call

Tail Recursion

```
(define (sum-to n)
  (cond
    [(zero? n) 0]
    [else (+ n (sum-to (sub1 n)))]))
```

The recursive call to `sum-to` is **not** in tail position

There's more work to do in `sum-to` after the recursive call

When Tail Recursion Matters

```
(define (run-server socket)
  (define-values (i o) (tcp-accept socket))
  (handle-connection i o)
  (run-sever socket))
```

The server shouldn’t leak memory as it handles connections

When Non-Tail Recursion Is Fine

```
(define (sum-list l)
  (cond
    [(empty? l) 0]
    [else (+ (first l)
             (sum-list (rest l)))]))
```

Uses O(n) space for a list of length n — but the list already uses O(n) space

Tail Position

More precisely, ***tail position*** is relative and inductively defined:

- `(lambda (`*`arg`*` ...) `*`tail-expr`*`)`

  i.e., *`tail-expr`* is in tail position w.r.t. the **`lambda`** form

- `(begin `*`expr`*` ... `*`tail-expr`*`)`
- `(if `*`expr`*` `*`tail-expr`*` `*`tail-expr`*`)`
- `(cond [`*`expr`*` `*`expr`*` ... `*`tail-expr`*`] ...)`
- `(and `*`expr`*` ... `*`tail-expr`*`)`
- `(or `*`expr`*` ... `*`tail-expr`*`)`

Tail Position

More precisely, ***tail position*** is relative and inductively defined:

- `(lambda (arg ...) tail-expr)`

  i.e., `tail-expr` is in tail position w.r.t. the `lambda` form

- `(begin expr ... tail-expr)`
- `(if expr tail-expr tail-expr)`

Proper tail-call handling:

a function call that is in *tail position* in a function body has the same continuation as the call to the function

It's "proper" because it's consistent with reduction as "ground truth"

Tail Calls

Tail calls need not be immediately recursive:

```
(define (is-even? n)
  (if (zero? n)
      #t
      (is-odd? (sub1 n))))

(define (is-odd? n)
  (if (zero? n)
      #f
      (is-even? (sub1 n))))
```

Tail Calls

Tail calls need not invoke a statically apparent target:

```
(define (check-arg f)
  (lambda (n)
    (unless (number? n) (error "bad"))
    (f n)))

(define (is-even? n)
  (if (zero? n)
      #t
      ((check-arg is-odd?) (sub1 n))))
```

“Improper” Tail Call Handling

```
int sumTo(int n, int a) {
  if (n == 0)
    return a;
  else
    return sumTo(n-1, n+a);
}
```

```
sumTo(10, 0)
→ return sumTo(9, 10)
→ return return sumTo(8, 19)
→ return return return sumTo(7, 27)
```

`sumTo(`n`, 0)` takes $O(n)$ space

which is bad, although it’s a less severe problem than a fixed-size stack

Tail-Call Workarounds

Languages without tail calls must provide additional syntactic support for tail recursion:

```
int sumTo(int n) {
  int a = 0;
  while (n != 0) {
    a = a+n;
    n = n-1;
  }
  return a;
}
```

Interlude: Loop Patterns in Racket

Recursion Patterns

A **`for`** loop is a good pattern for many purposes:

```
(for/fold ([a 0]) ([i n])
  (+ a i))
```

instead of

```
(let ()
  (define (loop a i)
    (if (= i n)
        a
        (loop (+ a i) (- n 1))))
  (loop 0 0))
```

Loop Variants

Imperative loops:

```
(for ([i seq])
  (do! i))
```

List creation:

```
(for/list ([i seq])
  (make-element i))
```

Any- and every-checks:

```
(for/and ([i seq])
  (ok? i))

(for/or ([i seq])
  (ok? i))
```

Accumulation:

```
(for/fold ([a 0]) ([i seq])
  (combine a i))
```

Space Safety

Space Complexity and Local Bindings

```
(define (f lon)
  (let ([lon2 (map add1 lon)])
    (+ (length lon2)
       (f (rest lon)))))
```

With C-like blocks:

```
(f (list .... n)) →→ (let ([lst2 (list .... n)])
                        (+ (length lst2)
                           (f (rest (list .... n)))))
                  →→ (let ([lst2 (list .... n)])
                        (+ n
                           (f (rest (list .... n)))))
                  →→ (let ([lst2 (list .... n)])
                        (+ n
                           (let ([lst2 (list .... n-1)])
                             (+ (length lst2)
                                (f (rest (list .... n-1)))))))
```

Space complexity would be $O(n^2)$

Space Complexity and Local Bindings

```
(define (f lon)
  (let ([lon2 (map add1 lon)])
    (+ (length lon2)
       (f (rest lon)))))
```

With substitution:

```
(f (list .... n)) →→ (let ([lst2 (list .... n)])
                        (+ (length lst2)
                           (f (rest (list .... n)))))
                  →→ (+ (length (list .... n))
                        (f (rest (list .... n))))
                  →→ (+ n
                        (f (rest (list .... n))))
                  →→ (+ n
                        (let ([lst2 (list .... n-1)])
                          (+ (length lst2)
                             (f (rest (list .... n-1))))))
```

Space complexity should be O(n)

Space Complexity and Local Bindings

```
(define (g lon)
  (+ (g (rest lon))
     (length lon)))
```

With simple substitution:

```
(g (list .... n)) → (+ (g (rest (list .... n)))
                       (length (list .... n)))
                  → (+ (g (list .... n-1))
                       (length (list .... n)))
                  → (+ (+ (g (rest (list .... n-1)))
                          (length (list .... n-1)))
                       (length (list .... n)))
                  → (+ (+ (g (list .... n-2))
                          (length (list .... n-1)))
                       (length (list .... n)))
```

Looks like $O(n^2)$, because the sharing of lists isn't shown

Space Complexity and Local Bindings

```
(define (g lon)
  (+ (g (rest lon))
     (length lon)))
```

With explicit allocation:

```
(g (list .... n)) →→ (begin
                       (define addrₙ (cons n empty))
                       (define addrₙ₋₁ (cons n-1 addrₙ))
                       ...
                       (g addr₁))
                  →→ (begin ....
                      (+ (g (rest addr₁))
                         (length addr₁)))
                  →→ (begin ....
                      (+ (+ (g (rest addr₂))
                            (length addr₂))
                         (length addr₁)))
```

Overall size (including definitions) is O(n)

Space Safety

Reduction semantics with explicit allocation is "ground truth" for Racket

The compiler and run-time system are ***safe for space***

i.e., consistent with ground truth, asymptotically

Space Safety and Language Extension

Space safety is particularly important in an extensible language:

```
#lang lazy

(define (list-from n)
  (cons n (list-form (add1 n))))

(define (has-negative? l)
  (if (negative? (car l))
      #t
      (has-negative? (rest l))))

(has-negative? (list-from 0))
```

constant-space behavior depends on not retaining the head of the infinite list

Summary

Functional programming ⇒ programming with algebra

- Proper tail-call handling and space safety enable reasoning about complexity via algebra

- Avoiding artificial resource constraints (such as stacks) make reasoning more uniform