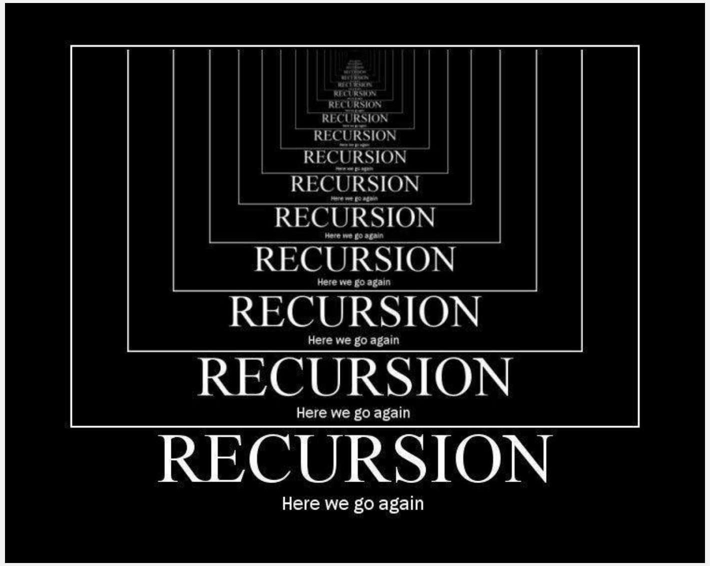
UMass Boston Computer Science

CS450 **High Level Languages**

Generative Recursion

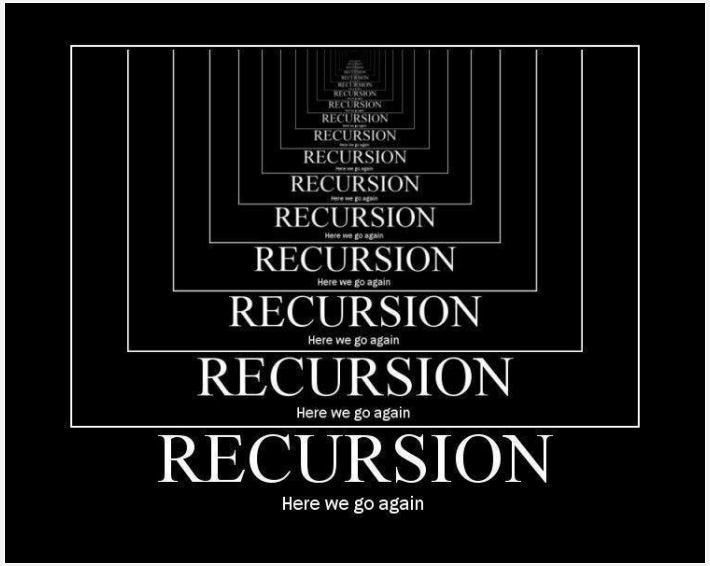
Tuesday, March 11, 2025



Logistics

- HW 5 in
  - ~~Due: **Tues 3/11 11am EST**~~
- HW 6 out
  - Due: **Tues 3/25 11am EST** (2 weeks)
- Reminder: **Spring Break next week!**
  - **No lecture**

(improper base case!)



Two-Argument Templates

Might need for HW6!
... use only when necessary!

Review

Htdp ch23

- Sometimes … a fn must **process <u>two</u> arguments simultaneously**
- **This template** should **combine templates of <u>both</u> args**
  - (This is only possible if the data defs are simple enough)

```
;; hit?: Ball Ball -> Boolean?
;; evaluates to true if the two Balls have overlap
```

(2-argument) TEMPLATE

```
(define (hit? b1 b2)
    ...   (ball-x b1) (ball-y b1)   ...
    ...   (ball-x b2) (ball-y b2)   ...
```

Ball **b1** template

Ball **b2** template

Must combine all these pieces together somehow …

```
;; hit?: Ball Ball -> Boolean?
;; evaluates to true if the two Balls have overlap
```

```
(define (hit? b1 b2)
      ...  (ball-x b1) (ball-y b1)  ...
      ...  (ball-x b2) (ball-y b2)  ...    )
```

Must combine all these pieces together somehow ...

```
;; hit?: Ball Ball -> Boolean?
;; evaluates to true if the two Balls have overlap
```

```
(define (hit? b1 b2)
 ... (dist (ball-x b1) (ball-y b1)
           (ball-x b2) (ball-y b2)) ...    )
```

Must combine all these pieces together somehow ...

```
;; hit?: Ball Ball -> Boolean?
;; evaluates to true if the two Balls have overlap
```

```
(define (hit? b1 b2)
  (< (dist (ball-x b1) (ball-y b1)
           (ball-x b2) (ball-y b2))
                    ...                          ))
```

```
;; hit?: Ball Ball -> Boolean?
;; evaluates to true if the two Balls have overlap
```

```
(define (hit? b1 b2)
  (< (dist (ball-x b1) (ball-y b1)
           (ball-x b2) (ball-y b2))
     (+ (ball-radius b1) (ball-radius b2))))
```

(assuming coordinates are center)

Recursion review

- Most **recursion** is **structural** (i.e., comes from **data definitions**)!

```
;; A List<X> is
;; - empty
;; - (cons X List<X>)
```

```
(define (lst-fn lst)
  (cond
   [(empty? lst) …]
   [else … (first lst) … (lst-fn (rest lst)) …]))
```

TEMPLATE

A Different Kind of Recursion!

- Not all **recursion** is **structural** (i.e., comes from **data definitions**)!

A Different Kind of Recursion!

- <u>Not all</u> recursion is **structural** (i.e., comes from **data definitions**)!

```
;; gcd : Nat Nat -> Nat
;; computes greatest common divisor, using Euclid's algorithm
;; termination argument:
;; m is halved (at least) eve                    ia modulo fn)
(define (gcd n m)
  (if (= m 0)
      n
      (gcd m (modulo n m))))
```

What template is this following??

A Different Kind of Recursion!

- **Non-structural recursion** (i.e., doesn't come from **data definitions**) is called **generative recursion**
- no template? … requires **Termination Argument**
  - Explains why the function terminates – because recursive call is "smaller"!

```
;; gcd : Nat Nat -> Nat
;; computes greatest common divisor, using Euclid's algorithm
;; termination argument:
;; m is halved (at least) every iteration (via mo
(define (gcd n m)
  (if (= m 0)
      n
      (gcd m (modulo n m))))
```

But how to develop an algorithm like this??

Recursive call must be on "smaller" version of the problem

Generative (non-structural) Recursion Design Recipe

1. Name, Signature
2. Description
   - Must include **Termination Argument**
3. Examples
   - Even more important now!
4. Code (No structural template, but can use a “general” template)
5. Tests

Generative (non-structural) Recursion Design Recipe

1. Name, Signature
2. Description
   - Must include **Termination Argument**
3. Examples
   - Even more important now!
4. Code (No structural template, but can use a “general” template)
   a) **Break problems into <u>smaller</u> problems to** (recursively) **solve**
   b) **Determine how to combine smaller solutions**
   c) **“trivially solvable” problem is base case!**
5. Tests

Generative (non-structural) Recursion Design Recipe

4. **Code** (No structural template, but can use a “general” template)
   a) **Break problems into smaller problems to** (recursively) **solve**
   b) **Determine how to combine smaller solutions**
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Generative (non-structural) Recursion Design Recipe

4. **Code** (No structural template, but can use a “general” template)
   a) **Break problems into smaller problems to (recursively) solve**
   b) Determine how to combine smaller solutions
   c) “trivially solvable” problem is base case!

```
;; genrec-algo: ??? -> ???
;; termination argument: recursive calls are “smaller” bc …
(define (genrec-algo problem)
  (cond
    [(trivial? problem) (solve-easy problem)] ;; base case
    [else (combine-solutions
             (genrec-algo (create-smaller-1 problem))
                …
             (genrec-algo (create-smaller-n problem)))]))
```

Generative (non-structural) Recursion Design Recipe

4. **Code** (No structural template, but can use a "general" template)
   a) Break problems into smaller problems to (recursively) solve
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Generative (non-structural) Recursion Design Recipe

4. **Code** (No structural template, but can use a "general" template)
   a) **Break problems into smaller problems to** (recursively) **solve**
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   c) **"trivially solvable" problem is base case!**

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              …
           (genrec-algo (create-smaller-n problem)))]))
```

GenRec Template Generalizes Structural!

```
(define (lst-fn lst)
  (cond
   [(empty? lst) …]
   [else … (first lst) … (lst-fn (rest lst)) …]))
```

- Trivial solution = data def base case
- Recursive smaller problem = data def smaller piece
- Left to figure out “Combining” pieces

```
;; genrec-algo: ??? -> ???

(define (genrec-algo problem)
  (cond
   [(trivial? problem) (solve-easy problem)] ;; base case
   [else (combine-solutions
           (genrec-algo (create-smaller-1 problem))
               …
           (genrec-algo (create-smaller-n problem)))]))
```

Previously

Generative Recursion Example!

(Functional) Quicksort

```
;; smaller-than: ListofInt Int -> ListofInt
;; Returns a list containing elements of given list
;; that are less than the given int
```

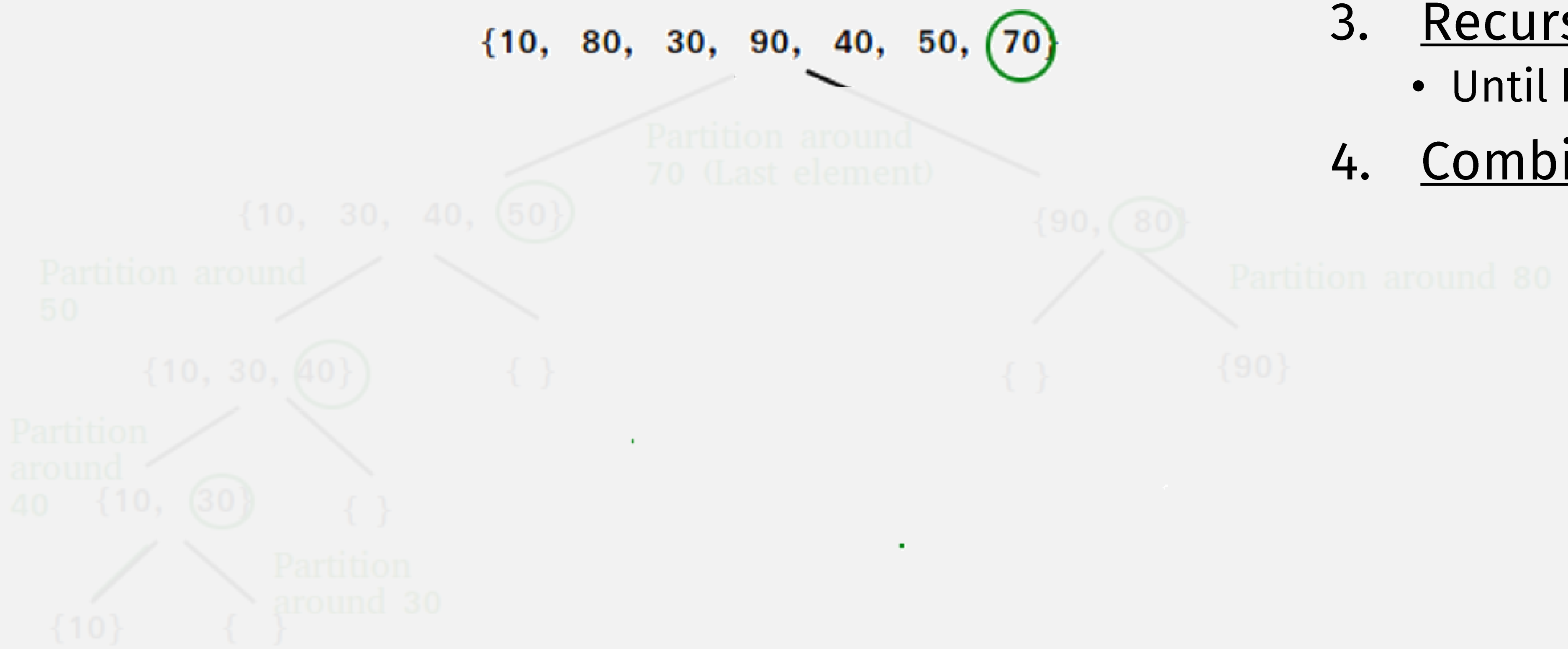
```
(check-equal?
  (smaller-than (list 1 3 4 5 9) 4)
                (list 1 3))
```

```
;; larger-than: ListofInt Int -> ListofInt
;; Returns a list containing elements of given list
;; that are greater than the given int
```

```
(check-equal?
  (greater-than (list 1 3 4 5 9) 4)
                (list 5 9))
```

```
;; qsort: ListofInt -> ListofInt
;; sorts the given list of ints in ascending order
(define (qsort lst)
  (define pivot (random lst))
  (append (qsort (smaller-than lst pivot))
          (list pivot)
          (qsort (greater-than lst pivot))))
```

Quicksort overview ("divide and conquer")



1. Choose "pivot" element
2. Partition into smaller lsts:
   - < pivot
   - >= pivot
3. Recurse on smaller lists
   - Until base case
4. Combine small solutions

Gen Rec Example: (functional) quicksort

1. Choose "pivot" element
2. Partition into smaller lsts:
   - < pivot
   - >= pivot
3. Recurse until base case
4. Combine small solutions

```
;; qsort: List<Int> -> List<Int>
;; termination argument:
;; recursive calls drop at least pivot
(define (qsort lst)
  (cond
   [(trivial? problem) (solve-easy lst)] ;; base case
   [else
    (define pivot (first lst))
    (combine-solutions
      (qsort (smaller-problem-1 lst))
               …
      (qsort (smaller-problem-n lst)))]))
```

Gen Rec Example: (functional) quicksort

1. Choose "pivot" element
2. Partition into smaller lsts:
   - < pivot
   - >= pivot
3. Recurse until base case
4. Combine small solutions

```
;; qsort: List<Int> -> List<Int>
;; terminati
;; r                                                  vot

  (c
    [(trivial? problem) (solve-easy lst)] ;
    [else
                              (first lst))
      (combine-solutions
        (qsort (filter (curry > pivot) (rest lst))
                          ...
        (qsort (filter (curry <= pivot) (rest lst)
```

Function "arithmetic"!

Result is a function!

```
(curry f arg1)
=
(lambda (arg2) (f arg1 arg2))
```

Curry = "partial apply"

```
(curry > pivot)
=
(lambda (x) (> pivot x))
```

"less than"

"greater than"

Gen Rec Example: (functional) quicksort

1. Choose "pivot" element
2. Partition into smaller lsts:
   - < pivot
   - >= pivot
3. Recurse until base case
4. Combine small solutions

```
;; qsort: List<Int> -> List<Int>
;; termination argument:
;; recursive calls drop at least pivot
(define (qsort lst)
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   [(trivial? problem) (solve-easy lst)] ;; base case
   [else
    (define pivot (first lst))
    (combine-solutions
      (qsort (filter (curry > pivot) (rest lst)))
                   …
      (qsort (filter (curry <= pivot) (rest lst)
```

"less than"

"greater than"

Gen Rec Example: (functional) quicksort

1. Choose "pivot" element
2. Partition into smaller lsts:
   - < pivot
   - >= pivot
3. Recurse until base case
4. Combine small solutions

```
;; qsort: List<Int> -> List<Int>
;; termination argument:
;; recursive calls drop at least pivot
(define (qsort lst)
  (cond
   [(empty? lst) empty] ;; base case
   [else
    (define pivot (first lst))
    (combine-solutions
      (qsort (filter (curry > pivot) (rest lst)))
                   …
      (qsort (filter (curry <= pivot) (rest lst))))]))
```

Gen Rec Example: (functional) quicksort

1. Choose "pivot" element
2. Partition into smaller lsts:
   - < pivot
   - >= pivot
3. Recurse until base case
4. Combine small solutions

```
;; qsort: List<Int> -> List<Int>
;; termination argument:
;; recursive calls drop at least pivot
(define (qsort lst)
  (cond
   [(empty? lst) empty] ;; base case
   [else
    (define pivot (first lst))
    (append
     (qsort (filter (curry > pivot) (rest lst)))
     (list pivot)
     (qsort (filter (curry <= pivot) (rest lst))))]))
```

Gen Rec Example: (functional) quicksort

```
;; qsort: List<Int> -> List<Int>
;; termination argument:
;; recursive calls “smaller” bc at least one item dropped (pivot)
(define (qsort lst)
  (cond
   [(empty? lst) empty] ;; base case
   [else
    (define pivot (first lst))
    (append
      (qsort (filter (curry > pivot) (rest lst)))
      (list pivot)
      (qsort (filter (curry <= pivot) (rest lst))))]))
```

Interlude: Recursion vs Iteration

- **Recursive** functions have a self-reference

```python
def factorialUsingRecursion(n):
    if (n == 0):
        return 1;

    # recursion call
    return n * factorialUsingRecursion(n - 1);
```

- **Iterative** code typically use a loop

```python
def factorialUsingIteration(n):
    res = 1;

    # using iteration
    for i in range(2, n + 1):
        res *= i;

    return res;
```

Recursion vs Iteration: Which is "Better"?

Recursive vs. Iterative Solutions

Recursive algorithms can be very space inefficient. Each recursive call adds a new layer to the stack, which means that if your algorithm recurses to a depth of n, it uses at least O(n) memory.

For this reason, it's often better to implement a recursive algorithm iteratively. *All* recursive algorithms can be implemented iteratively, although sometimes the code to do so is much more complex. Before diving into recursive code, ask yourself how hard it would be to implement it iteratively, and discuss the tradeoffs with your interviewer.

Cracking the Coding Interview, Ch8

r/learnprogramming • 11 yr. ago

[Best Practices] Recursion. Why is it generally avoided and when is it acceptable?

stackoverflow

Are recursive methods always better than iterative methods in Java?

Recursion vs Iteration: Conventional Wisdom

Iteration

Strengths:

- Iteration can be used to repeatedly execute a set of statements without the overhead of function calls and without using stack memory.
- Iteration is faster and more efficient than recursion.
- It's easier to optimize iterative codes, and they generally have polynomial time complexity.
- They are used to iterate over the elements present in data structures like an array, set, map, etc.
- If the iteration count is known, we can use *for* loops; else, we can use *while* loops, which terminate when the controlling condition becomes false.

Weaknesses:

- In loops, we can go only in one direction, i.e., we can't go or transfer data from the current state to the previous state that has already been executed.
- It's difficult to traverse trees/graphs using loops.
- Only limited information can be passed from one iteration to another, while in recursion, we can pass as many parameters as we need.

Iteration is good with *non-recursive data*

Iteration is bad with *recursive data*!

Recursion better when **accumulators** are needed

https://www.interviewkickstart.com/learn/difference-between-recursion-and-iteration

Recursion vs Iteration: Conventional Wisdom

Recursion

Strengths:

- It's easier to code the solution using recursion when the solution of the current problem is dependent on the solution of smaller similar problems.
  - fibonacci(n) = fibonacci(n-1) + fibonacci(n-2)
  - factorial(n) = n * factorial(n-1)
- Recursive codes are smaller and easier to understand. ☑
- We can pass information to the next state in the form of parameters and return information to the previous state in the form of the return value.
- It's a lot easier to perform operations on trees and graphs using recursion.

Weaknesses:

- The simplicity of recursion comes at the cost of time and space efficiency.
- It is much slower than iteration due to the overhead of function calls and control shift from one function to another.
- It requires extra memory on the stack for each recursive call. This memory gets deallocated when function execution is over.
- is difficult to optimize a recursive code, and they generally have higher time complexity an iterative codes due to overlapping subproblems.

Recursion better when **accumulators** are needed

Use recursion with *recursive data*!

Recursion is slow

Recursion is slow

Recursion is slow

Recursion is slow

Investigate:

Is recursion is slower??

https://www.interviewkickstart.com/learn/difference-between-recursion-and-iteration

Recursion vs Iteration: In Racket

Racket Recursion

```
;; sum-to : Nat -> Nat
;; Sums the numbers in the interval [0, x]
(define (sum-to x)
  (if (zero? x)
      x
      (+ x (sum-to (sub1 x)))))
```

```
(define BIG-NUMBER 999999)

(time (sum-to BIG-NUMBER))
; cpu time: 202 real time: 201 gc time: 156
```

Conclusion?

Recursion is slower?

WAIT!

Racket does not have “for” loops

Racket “Iteration”

```
(time (for/sum ([x (add1 BIG-NUMBER)]) x))
; cpu time: 15 real time: 6 gc time: 0
```

Recursion vs Iteration: In Racket

Conclusion?
Recursion is not slower than iteration?

Racket Recursion

```
;; iterative-sum-to : Nat -> Nat
;; Sums the numbers in the interval [0, x]
(define (iterative-sum-to x result)
  (if (zero? x)
      result
      (iterative-sum-to (sub1 x) (+ x result))))
```

accumulator

equivalent

```
(time (iterative-sum-to BIG-NUMBER 0))
; cpu time: 15 real time: 13 gc time: 0
```

Racket "Iteration"

```
(time (for/sum ([x (add1 BIG-NUMBER)]) x))
; cpu time: 15 real time: 6 gc time: 0
```

"for" in Racket is just a macro (i.e., "syntactic sugar") for a recursive function

Tail Calls

From Wikipedia, the free encyclopedia

In computer science, a **tail call** is a subroutine call performed as the final action of a procedure. If the target of a tail is the same subroutine, the subroutine is said to be **tail recursive**, which is a special case of direct recursion. **Tail recursion** (or **tail-end recursion**) is particularly useful, and is often easy to optimize in implementations.

Tail calls can be implemented without adding a new stack frame to the call stack.

Recursion vs Iteration: In Racket

Racket Recursion

Conclusion?

Recursion is not slower than iteration?

```
;; iterative-sum-to : Nat -> Nat
;; Sums the numbers in the interval [0, x]
(define (iterative-sum-to x result)
  (if (zero? x)
      result
      (iterative-sum-to (sub1 x) (+ x result))))
```

Tail-recursive function

Tail-call (does not add to stack)

(Tail) recursion is iteration!

Recursion vs Iteration: Under the Hood

- **It makes sense that recursion** and **iteration** are **equivalent …**
  - Recursive call compiles to:
    - `JUMP` instruction
  - Loop compiles to:
    - `JUMP` instruction!

- … except in languages that make them not equivalent!
  - i.e., languages that push extra stack frames that are not needed

Tail-Calls in Other Languages

- Most functional languages (RACKET, HASKELL, ERLANG, F#) implement proper tail calls
  (no extra stack frame)

- Some languages require an explicit annotation
  - CLOJURE: `recur`
  - SCALA: `@tailrec`

- Some languages (JAVASCRIPT) have it (ECMASCRIPT 6), but don't have it

- Most imperative languages don't properly implement tail calls
  (they add an unnecessary stack frame)
  - PYTHON, JAVA, C#, GO

Guido Got It Backwards

Wednesday, April 22, 2009

Tail Recursion Elimination

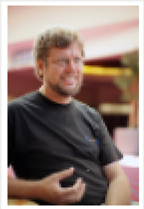
I recently posted an entry in my Python History blog on the origins of Python's functional features. A side remark about not supporting tail recursion elimination (TRE) immediately sparked several comments about what a pity it is that Python doesn't do this, including links to recent blog entries by others trying to "prove" that TRE can be added to Python easily. So let me defend my position (which is that I don't *want* TRE in the language). If you want a short answer, it's simply unpythonic. Here's the long answer:

Wrong!

First, as one commenter remarked, TRE is incompatible with nice stack traces: when a tail recursion is eliminated, there's no stack frame left to use to print a traceback when something goes wrong later. This will confuse ...ently wrote something recursive (the recursion isn't obviou... ...ce printed), and makes debugging hard. Providing an optio... ...eems wrong to me: Python's default is and should always b... be maximally helpful for debugging. This also brings me to the next issu...

Equivalent to saying:
"every **for** loop iteration should push a stack frame!"

About Me



Guido van Rossum

Python's BDFL

View my complete profile

Blog Archive

▶ 2022 (2)

▶ 2019 (1)

Proper tail calls is about **eliminating stack frames** that **<u>shouldn't be there in the first place!</u>** (because it's just iteration!)

Non Tail Call

C

```c
// Program to find factorial of a number n modulo prime
int factorial(int n, int prime)
{
    if (n <= 1) {
        // base case
        return 1;
    }

    return (n * factorial(n - 1, prime) % prime) % prime;
}
```

Non-tail-call

Slower, more memory

Compiler output:
godbolt.org

x86-64 gcc 14.2 -O3

```asm
factorial:
  cmp edi, 1
  jle .L16
  push r15
  mov eax, 2
  push r14
  push r13
  push r12
  lea r12d, [rdi-1]
  push rbx
  mov ebx, edi
  sub rsp, 16
  cmp edi, 2
  je .L3
  lea r13d, [rdi-2]
  cmp edi, 3
  je .L4
  lea r15d, [rdi-3]
  cmp edi, 4
  je .L5
  lea r14d, [rdi-4]
  cmp edi, 5
  je .L6
  lea edi, [rdi-5]
  mov DWORD PTR [rsp+12], esi
  call factorial
  mov esi, DWORD PTR [rsp+12]
  imul eax, r14d
  cdq
  idiv esi
  mov eax, edx
  imul eax, r15d
.L6:
  cdq
  idiv esi
  mov eax, edx
  imul eax, r13d
.L5:
  cdq
  idiv esi
  mov eax, edx
  imul eax, r12d
.L4:
  cdq
  idiv esi
```

Stack push

https://www.geeksforgeeks.org/tail-call-optimisation-in-c/

Compiler output: godbolt.org

x86-64 gcc 14.2 -O3

C

Tail Calls as Loops

```c
// C program to illustrate Tail Call Optimisation
int factorial(int store, int num, int prime) {
  if (num < 1) {
    // Base case
    return store;
  }

  return factorial((store%prime * num%prime)%prime, num - 1, prime);
}
```

Tail call – compiled directly to **for** loop!

Faster, less memory

```c
// this function calculates factorial modulo prime
int factorial(int num, int prime) {
    int store = 1;
    for (int i = num; i > 0; i--) {
        store = (store%prime * i%prime)%prime;
    }
  return store;
}
```

for loop

```asm
factorial(int, int, int):
  mov ecx, edx
  test esi, esi
  jle .L5
.L2:
  mov eax, edi
  cdq
  idiv ecx
  mov eax, edx
  imul eax, esi
  cdq
  idiv ecx
  mov edi, edx
  sub esi, 1
  jne .L2
.L5:
  mov eax, edi
  ret
```

```asm
factorial(int, int):
  mov edx, 1
  test edi, edi
  jle .L1
.L3:
  mov eax, edx
  cdq
  idiv esi
  mov eax, edx
  imul eax, edi
  cdq
  idiv esi
  sub edi, 1
  jne .L3
.L1:
  mov eax, edx
  ret
```

No stack push!

Recursion is same as **for** loop!

Some languages (with –O3 optimization) **directly compile recursion to a loop!** (because they are equivalent!)

Proper Tail Calls in JavaScript

Proper Tail Calls (PTC) is a new feature in the ECMAScript 6 language. This feature was added to facilitate recursive programming patterns, both for direct and indirect recursion. Various other design patterns can benefit from PTC as well, such as code that wraps some functionality where the wrapping code directly returns the result of what it wraps. Through the use of PTC, the amount of memory needed to run code is reduced. In deeply recursive code, PTC enables code to run that would otherwise throw a stack overflow exception.

https://webkit.org/blog/6240/ecmascript-6-proper-tail-calls-in-webkit/

Not supported in V8 (Chrome) or SpiderMonkey (Firefox)!

Compilers/polyfills

Feature name	Babel 7 + core-js 3	Closure 2023.02	Type-Script + core-js 3	es6-shim
	72%	55%	69%	17%
proper tail calls (tail call optimisation)	0/2	0/2	0/2	0/2

Desktop browsers

Feature name	Kong 4.14[1]	IE 11	FF 115 ESR	FF 120	FF 121	FF 122	CH 116	CH 117	CH 118 Beta	CH 119 Dev	CH 120 Canary	Edge 113	Edge 114	SF 16.6	SF 17.0	SF TP	WK	OP 98	OP 99
	5%	11%	98%	98%	98%	98%	98%	98%	98%	98%	98%	98%	98%	100%	100%	100%	99%	98%	98%
proper tail calls (tail call optimisation)	0/2	0/2	0/2	0/2	0/2	0/2	0/2	0/2	0/2	0/2	0/2	0/2	0/2	2/2	2/2	2/2	2/2	0/2	0/2

Servers/runtimes

Feature name	Echo JS	XS6	JXA	Node >=16.11 <17	Node >=18.3 <19	Node >=19.2 <20	Node >=20	DUK 2.7	JrS 2.4.0	JJS 1.8	GraalVM 21.3.3[5]	GraalVM 22.2.0[5]	Hermes 0.12.0	Deno 1.36
	65%	94%	58%	98%	98%	98%	98%	26%	96%	7%	98%	98%	74%	98%
proper tail calls (tail call optimisation)	0/2	2/2	0/2	0/2	0/2	0/2	0/2	2/2	0/2	0/2	0/2	0/2	0/2	0/2

Mobile

Feature name	iOS 17.0	Samsung 22	Opera Mobile 77
	100%	98%	98%
proper tail calls (tail call optimisation)	2/2	0/2	0/2

https://compat-table.github.io/compat-table/es6/

Recursion vs Iteration: Conclusion

Recursion

Strengths:

- It's easier to code the solution using recursion when the solution of the current problem is dependent on the solution of smaller similar problems.
  - fibonacci(n) = fibonacci(n-1) + fibonacci(n-2)
  - factorial(n) = n * factorial(n-1)
- Recursive codes are smaller and easier to understand.
- We can pass information to the next state in the form of parameters and return information to the previous state in the form of the return value.
- It's a lot easier to perform operations on trees and graphs using recursion.

Weaknesses:

- The simplicity of recursion comes at the cost of time and space efficiency.
- It is much slower than iteration due to the overhead of function calls and control shift from one function to another.
- It requires extra memory on the stack for each recursive call. This memory gets deallocated when function execution is over.
- It is difficult to optimize a recursive code, and they generally have higher time complexity than iterative codes due to overlapping subproblems.

Recursion better when **accumulators** are needed

Recursion is (usually) easier to read

Use recursion with *recursive data*!

Recursion is slower ...

... in languages that choose to make it slower!

`https://www.interviewkickstart.com/learn/difference-between-recursion-and-iteration`