Tail calls

Advanced Compiler Construction
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Tail calls

(and their elimination)

Functional loops

Often, functional languages do not offer loops.

So, programmers resort to recursion.

E.g., the central loop of an L_3 Web server might be:

```
(defrec web-server-loop
  (fun ()
    (wait-for-connection)
    (fork handle-connection)
    (web-server-loop)))
```

Recursion problem

Problem:

- recursive calls consume stack,
- the web server will eventually crash (stack overflow).

But:

- the call to `web-server-loop` could be a jump!

So, the compiler should:

- detect such calls,
- replace them by jumps.

Tail calls

Why can the recursive call of `web-server-loop` be replaced by a jump?

Because it is the last action taken by the function:

```
 (defrec web-server-loop
   (fun ()
     (wait-for-connection)
     (fork handle-connection)
     (web-server-loop)))
```

Such a call in terminal position is a **tail call** (this one is also recursive, but not all are).

Exercise

In the L_3 functions below, which calls are tail calls?

```
(defrec list-map
  (fun (f l)
     (if (list-empty? l)
         l
         (list-prepend
           (f (list-head l))
           (list-map f (list-tail l))))))
(defrec list-fold-left
  (fun (f z l)
     (if (list-empty? l)
         z
         (list-fold-left f
                         (f z (list-head l))
                         (list-tail l)))))
```

Tail call elimination

When a function performs a tail call, its own activation frame is dead: it won't be used anymore, as there is nothing to do after the call returns.

Therefore tail calls can be compiled as:

1. load the arguments for the callee,
2. free the activation frame of the caller,
3. *jump* (!) to the callee.

This is called **tail call elimination** (or **optimization**).

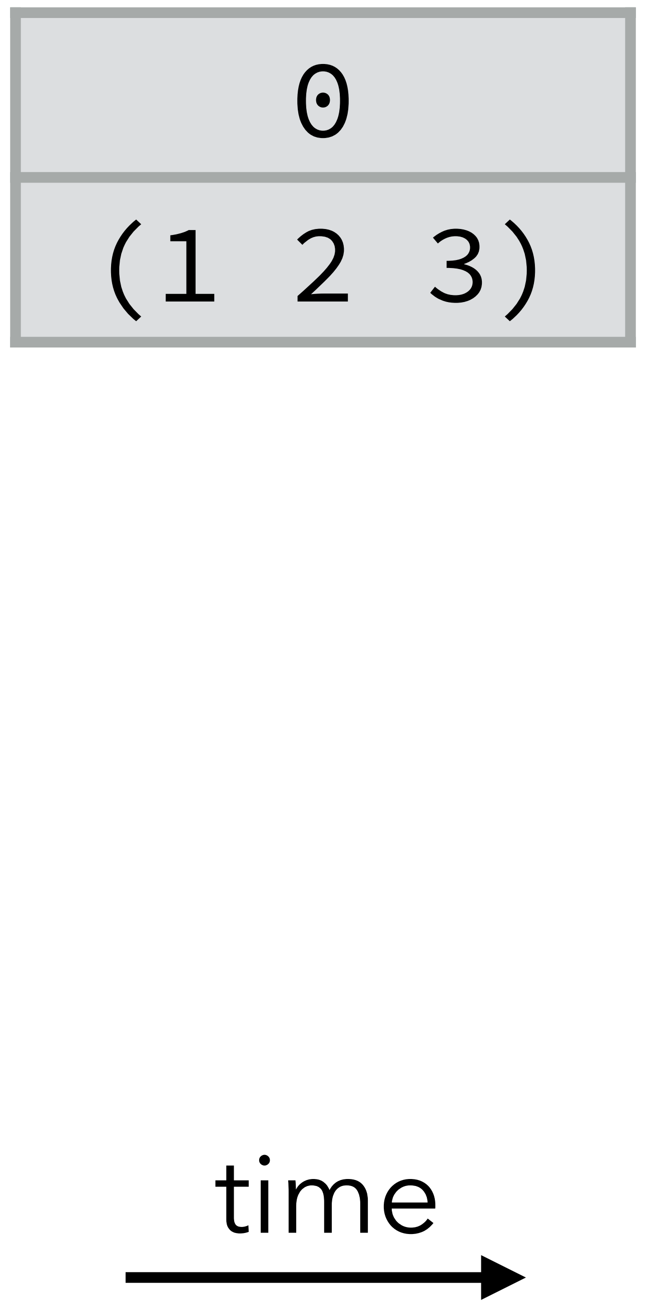
TCE example

Consider the following function definition and call:

```
(defrec sum
  (fun (z l)
    (if (list-empty? l)
        z
        (sum (+ z (list-head l))
             (list-tail l)))))
(sum 0 (list-make 1 2 3))
```

How does the stack evolve, with and without tail call elimination?

Stack evolution (no TCE)

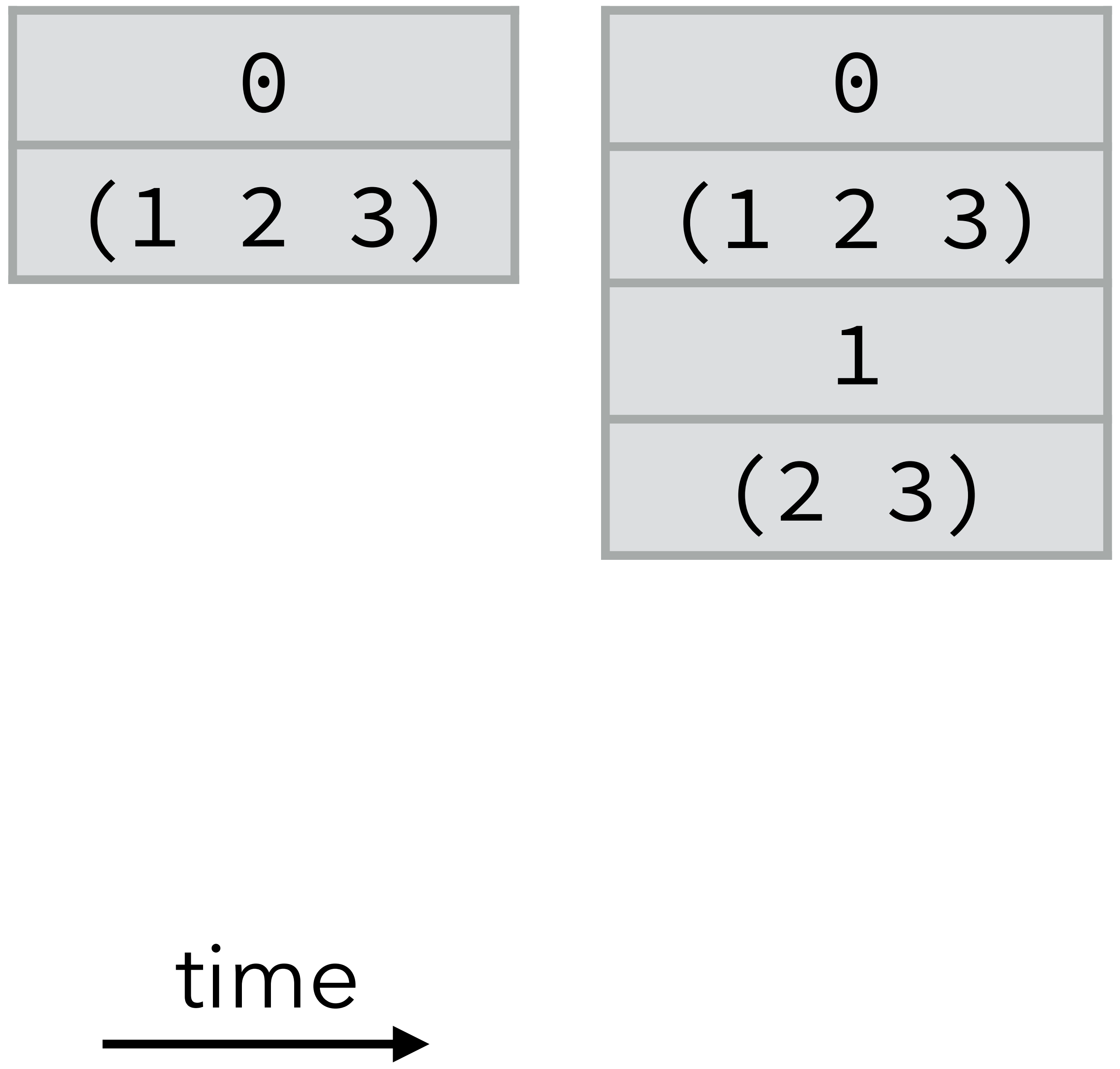


0

(1 2 3)

time

Stack evolution (no TCE)



0

(1 2 3)

0

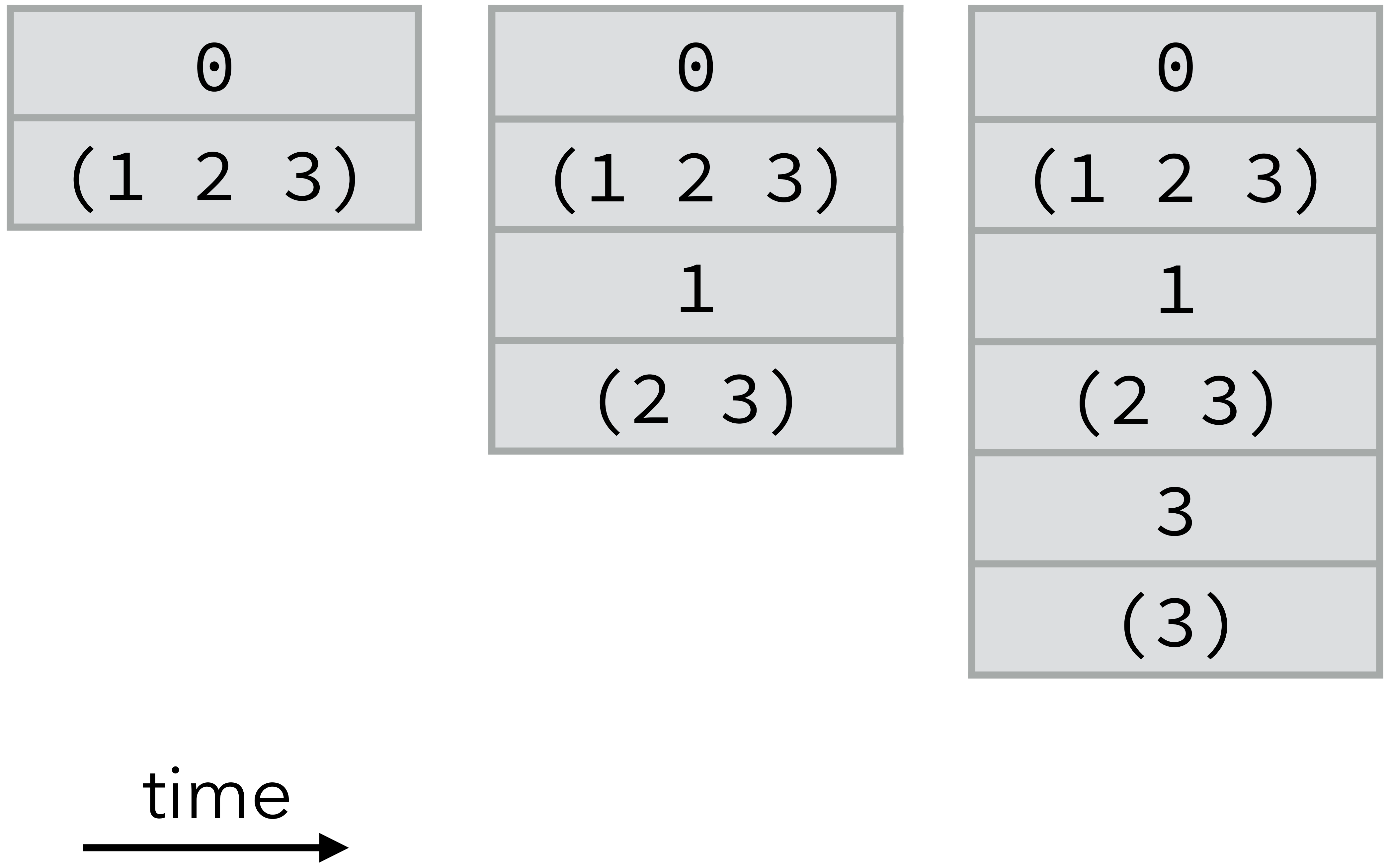
(1 2 3)

1

(2 3)

time

Stack evolution (no TCE)



0

(1 2 3)

0

(1 2 3)

1

(2 3)

0

(1 2 3)

1

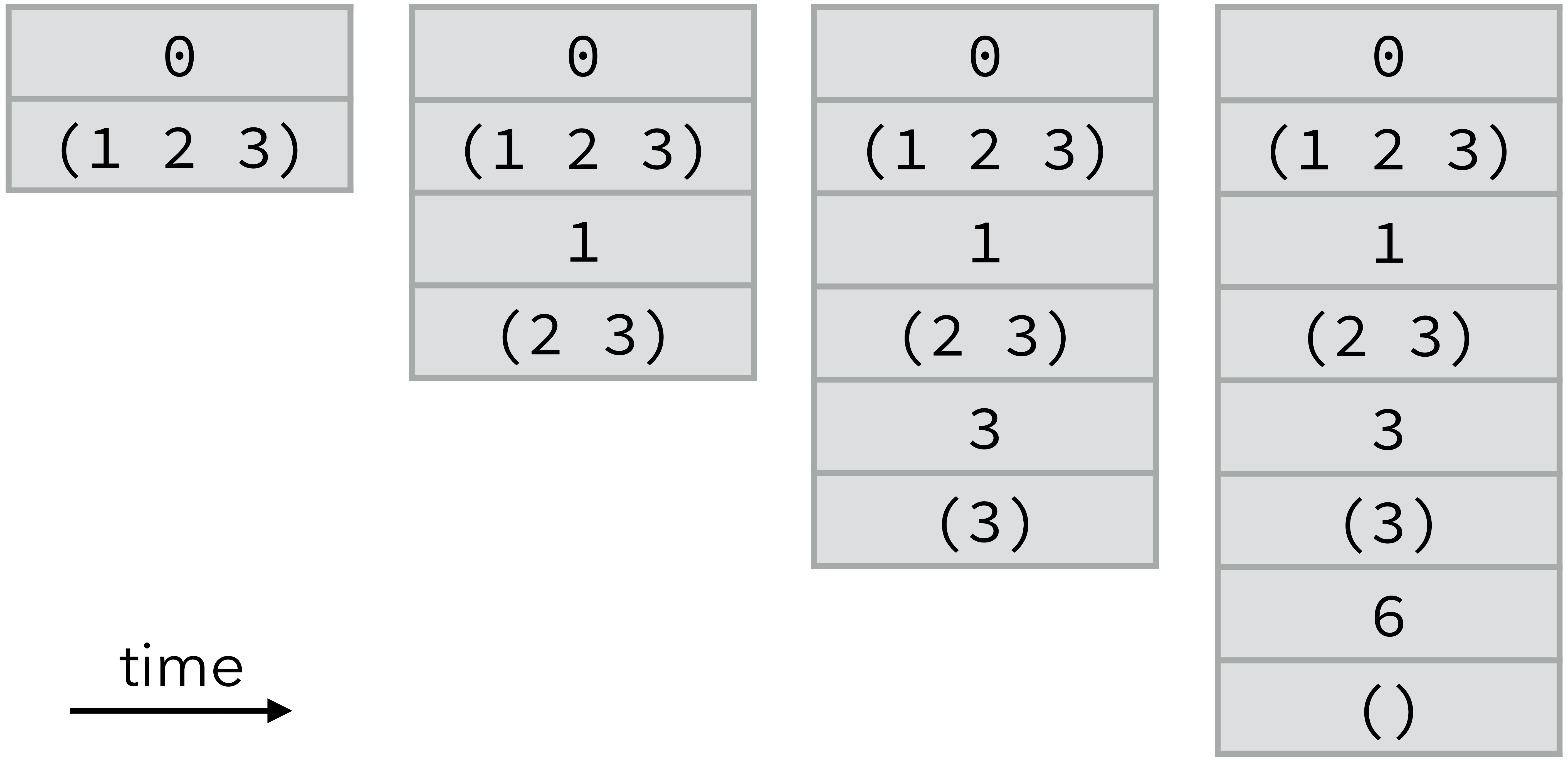
(2 3)

3

(3)

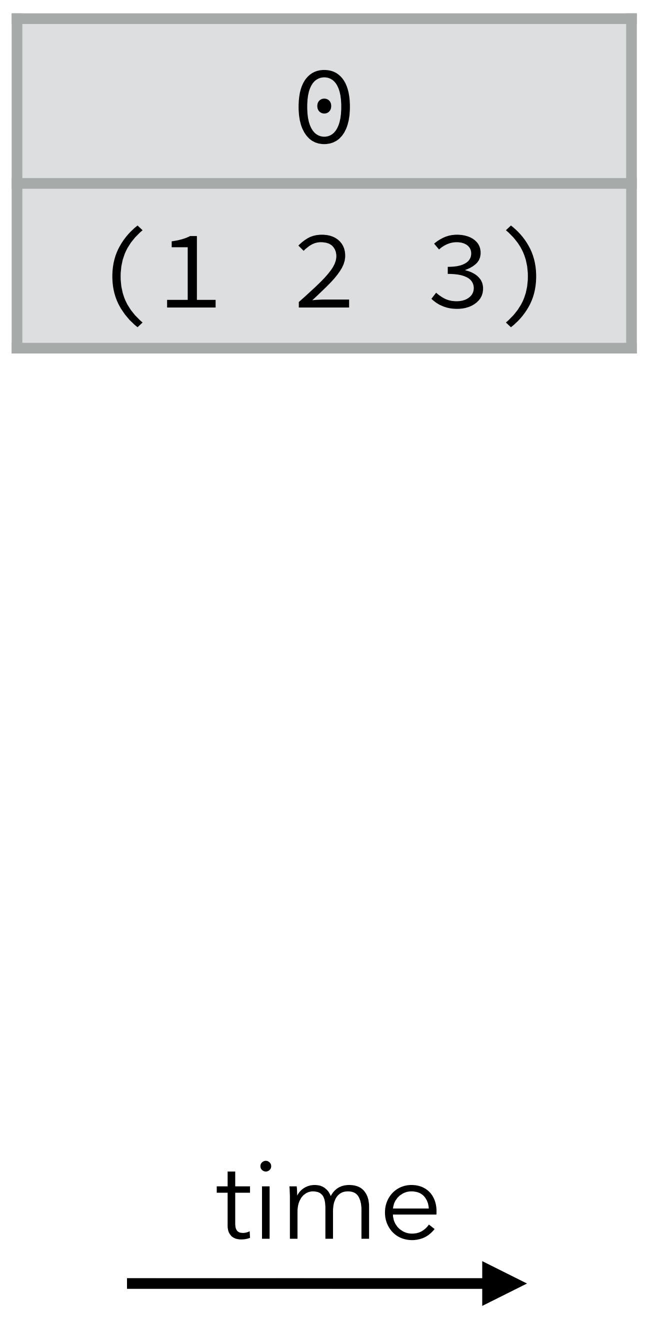
time

Stack evolution (no TCE)

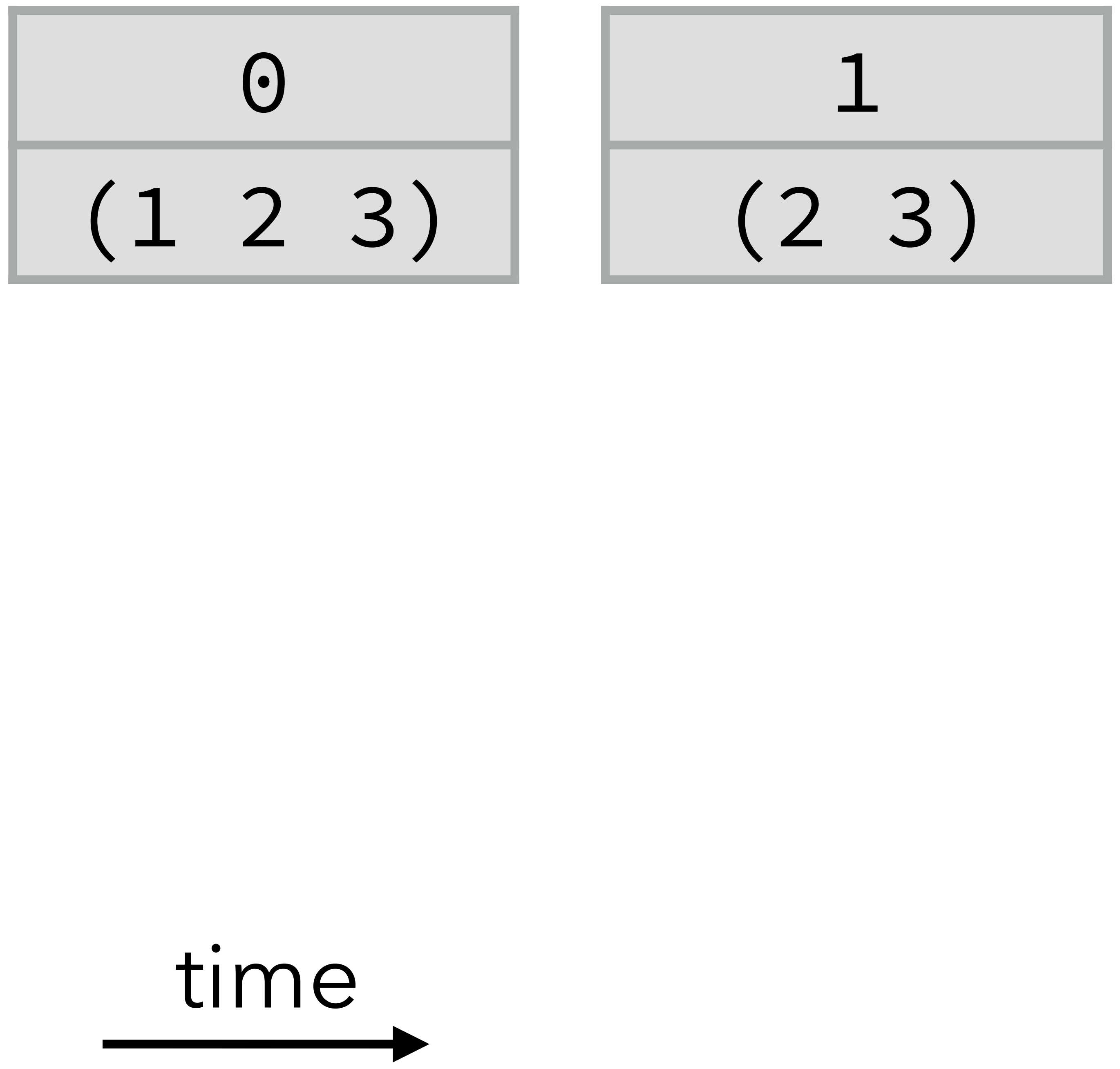


0	0	0	0
(1 2 3)	(1 2 3)	(1 2 3)	(1 2 3)
	1	1	1
	(2 3)	(2 3)	(2 3)
		3	3
		(3)	(3)
			6
			()

Stack evolution (TCE)



Stack evolution (TCE)

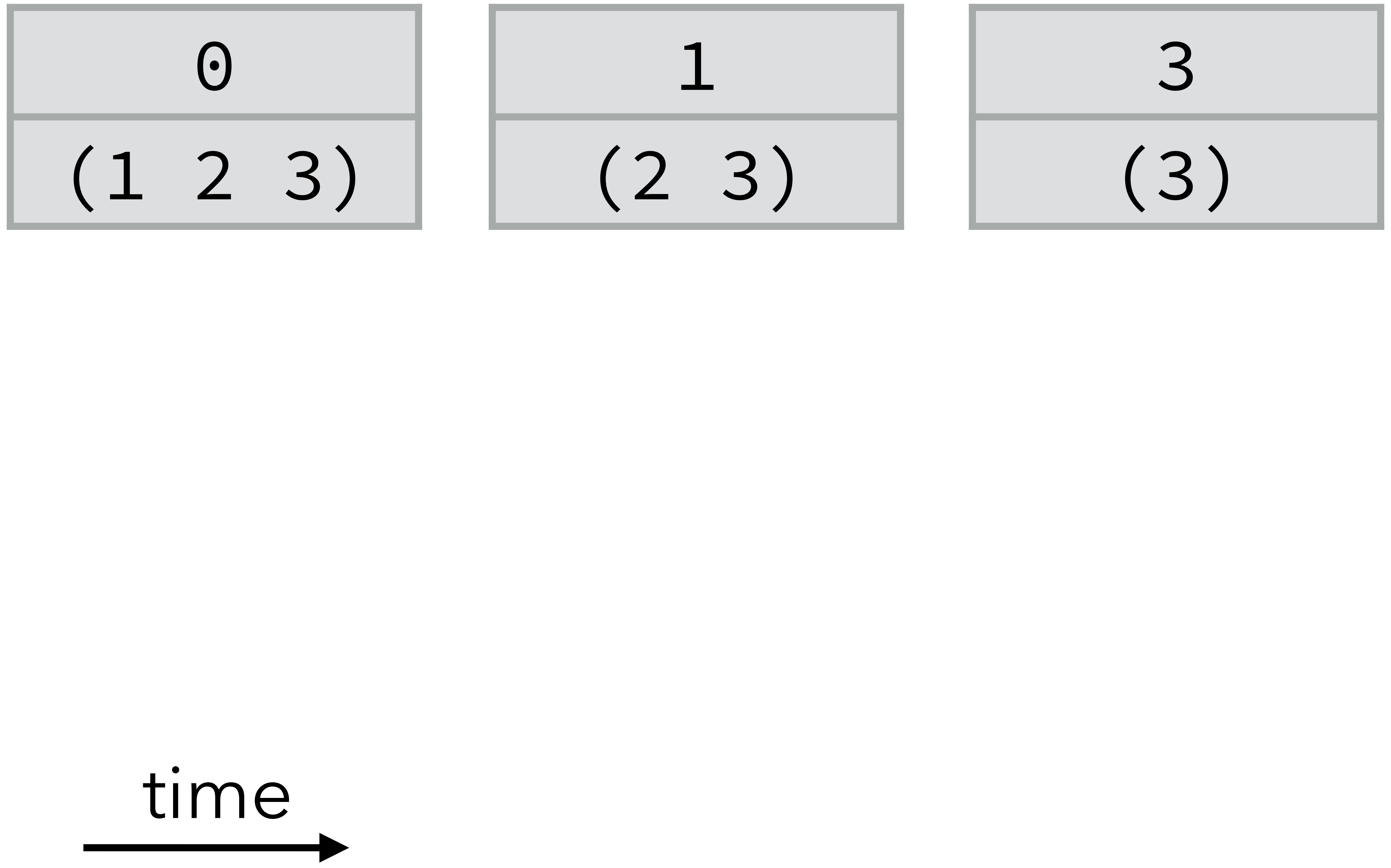


```
0
(1 2 3)
```

```
1
(2 3)
```

time

Stack evolution (TCE)



0

(1 2 3)

1

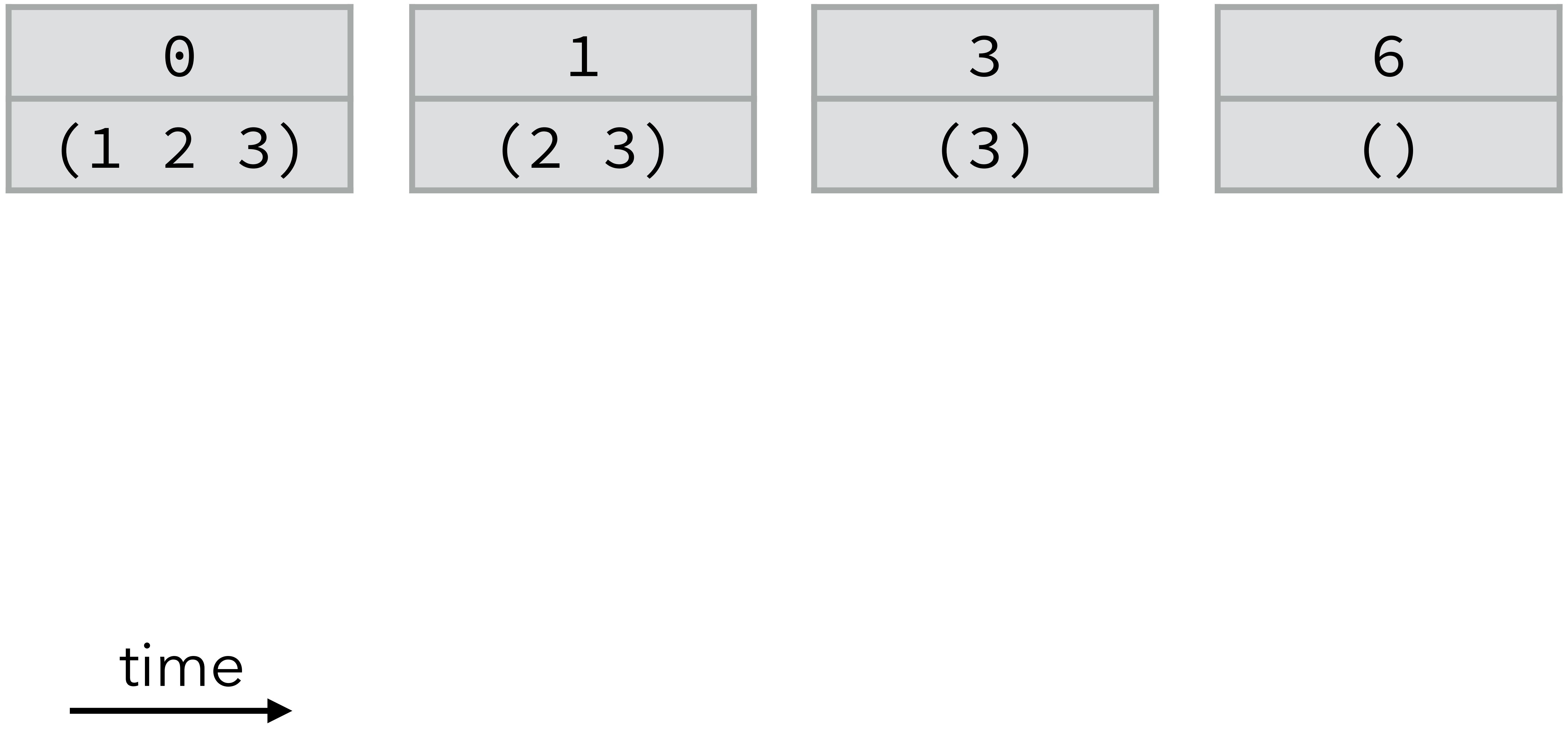
(2 3)

3

(3)

time

Stack evolution (TCE)



Tail call *optimization*?

Tail call elimination is more than just an optimization: one cannot write endless recursive loops without it.

Therefore:

- some language specifications (e.g. Scheme's) *require* that conforming implementations do TCE,
- other language specification (e.g. C's) don't, so compiler authors choose whether to do TCE or not.

Tail calls in L_3

Translation of L$_3$ tail calls

Reminder: the basic translation from CL$_3$ to CPS/L$_3$ doesn't handle tail calls specially, and translates them sub-optimally.

E.g., the CL$_3$ term:

```
(letrec ((f (fun (g) (g)))) f)
```

gets translated to the CPS/L$_3$ term:

```
(let_f ((f (fun (r_1 g)
             (let_c ((r_2 (cnt (v)
                            (app_c r_1 v))))
               (app_f g r_2)))))
  f)
```

in which the tail call from `f` to `g` returns to `f` – since its return continuation is `r`$_2$ – instead of directly returning to its caller.

Translation of L$_3$ tail calls

The improved translation from CL$_3$ to CPS/L$_3$ does handle tail calls specially, and optimizes them correctly.

With it, the same CL$_3$ term as before:

```
(letrec ((f (fun (g) (g)))) f)
```

gets translated to the CPS/L$_3$ term:

```
(let_f ((f (fun (r_1 g) (app_f g r_1))))
  f)
```

in which the tail call to `g` is optimized, in that it gets the same return continuation r_1 as `f` itself.

Translation of L_3 tail calls

Non-tail calls are handled by $\llbracket\cdot\rrbracket_N$, as follows:

$\llbracket$ (e e_1 e_2 …) $\rrbracket_N$ C =

$\llbracket e\rrbracket_N(\lambda v\ \llbracket e_1\rrbracket_N(\lambda v_1\ \llbracket e_2\rrbracket_N(\lambda v_2$ …

(let$_c$ (($\underline{c}$ (cnt (r) C[r])))

(app$_f$ v c v_1 v_2 …))))))

while tail calls are handled by $\llbracket\cdot\rrbracket_T$, as follows:

$\llbracket$ (e e_1 e_2 …) $\rrbracket_T$ c =

$\llbracket e\rrbracket_N(\lambda v\ \llbracket e_1\rrbracket_N(\lambda v_1\ \llbracket e_2\rrbracket_N(\lambda v_2$ …

(app$_f$ v c v_1 v_2 …))))

Translation of CPS/L_3 tail calls

In the L_3 compiler, CPS/L_3 is just an IR, not the target language.

So, when generating target code, tail calls must be identified and translated appropriately.

This is trivial:

- a call where the callee gets the caller's return continuation is a tail call,
- all other calls are non tail calls.

TCE in uncooperative environments

TCE in various environments

Doing TCE requires support from the target language, to deallocate the stack frame and do the jump:

- no problem when generating machine code,
- much harder when generating C code, or JVM bytecode.

Several techniques exist to do TCE in these so-called "uncooperative environments".

Benchmark program

The techniques will be illustrated using the simple C program below. If the C compiler does not do TCE, it crashes with a stack overflow.

```c
int even(int x){ return x == 0 ? 1 : odd(x-1); }
int odd(int x){ return x == 0 ? 0 : even(x-1); }
int main(int argc, char* argv[]) {
  printf("%d\n", even(300000000));
}
```

Single-function approach

Single function approach:

- compile the whole program to a single target function,
- tail calls become local jumps,
- other calls become recursive calls to that function.

Often difficult to apply in practice, due to limitations in the size of functions of the target language.

Single function in C

```c
typedef enum { fun_even, fun_odd } fun_id;
int wholeprog(fun_id fun, int x) {
  switch (fun) {
  case fun_even: goto even;
  case fun_odd:  goto odd;
  }

 even:
  if (x == 0) return 1;
  x = x - 1;
  goto odd;
 odd:
  if (x == 0) return 0;
  x = x - 1;
  goto even;
}
int main(int argc, char* argv[]) {
  printf("%d\n", wholeprog(fun_even, 300000000));
}
```

Trampolines

Trampoline technique:

- functions never perform tail calls directly,
- rather, they return a special value to their caller – freeing their stack frame in the process,
- the caller does the call on their behalf.

This requires checking the return value of all function, to see whether a tail call must be performed. The code which performs this check is called a **trampoline**.

Trampolines in C

```c
typedef void* (*fun_ptr)(int);
struct { fun_ptr fun; int arg; } resume;
void* even(int x) {
  if (x == 0) return (void*)1;
  resume.fun = odd;
  resume.arg = x - 1;
  return &resume;
}
void* odd(int x) {
  if (x == 0) return (void*)0;
  resume.fun = even;
  resume.arg = x - 1;
  return &resume;
}
int main(int argc, char* argv[]) {
  void* res = even(300000000);
  while (res == &resume)
    res = (resume.fun)(resume.arg);
  printf("%d\n",(int)res);
}
```

Extended trampolines

Extended trampoline technique:

- similar to trampolines, but trade some space for speed,
- do not return to trampoline on *every* tail call,
- rather, wait until a given number of successive ones happened, then return (non locally).

Non-local returns in C

Extended trampolines require non-local returns.

In C, they can be performed using `setjmp` and `longjmp`, a kind of `goto` that works across functions:

- `setjmp(b)` saves its calling environment in b, and returns 0,
- `longjmp(b, v)` restores the environment stored in b, and proceeds as if the call to `setjmp` had returned v instead of 0.

Extended trampolines in C

```c
typedef int (*fun_ptr)(int, int);
struct { fun_ptr fun; int arg; } resume;
jmp_buf jmp_env;

int even(int tcc, int x) {
  if (tcc > TC_LIMIT) {
    resume.fun = even;
    resume.arg = x;
    longjmp(jmp_env, -1);
  }
  return (x == 0) ? 1 : odd(tcc + 1, x - 1);
}
int odd(int tcc, int x) { /* similar to even */ }

int main(int argc, char* argv[]) {
  int res = (setjmp(jmp_env) == 0)
    ? even(0, 300000000)
    : (resume.fun)(0, resume.arg);
  printf("%d\n",res);
}
```

Baker's technique

Baker’s technique:

- transform the whole program to continuation passing style (CPS),
- consequence: all calls are tail calls,
- so the *whole* stack can be shrunk periodically using a non-local return.

Baker's technique in C

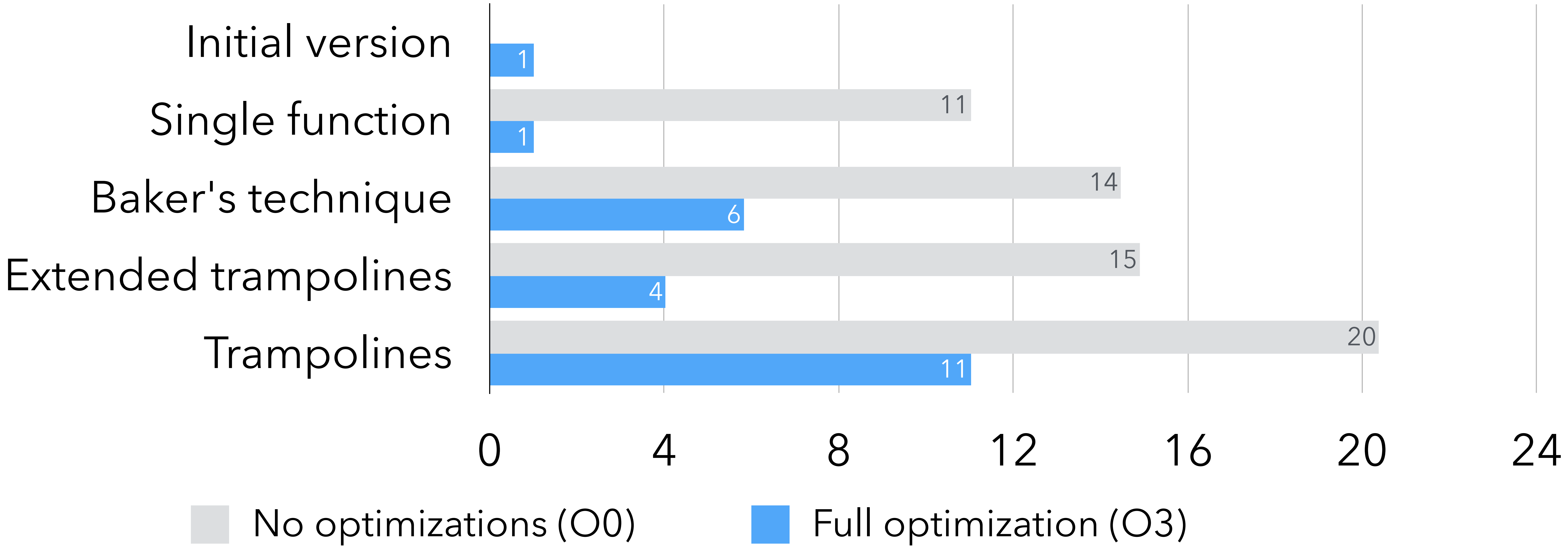
```c
typedef void (*cont)(int);
typedef void (*fun_ptr)(int, cont);
int tcc = 0;
struct { fun_ptr fun; int arg; cont k; } resume;
jmp_buf jmp_env;
void even_cps(int x, cont k) {
  if (++tcc > TC_LIMIT) {
    tcc = 0;
    resume.fun = even_cps;
    resume.arg = x;
    resume.k = k;
    longjmp(jmp_env, -1);
  }
  if (x == 0) (*k)(1); else odd_cps(x - 1, k);
}
void odd_cps(int x, cont k) { /* similar to even_cps */ }
int main(int argc, char* argv[]) {
  if (setjmp(jmp_env) == 0) even_cps(300000000, main_1);
  else (resume.fun)(resume.arg, resume.k);
}
void main_1(int val) { printf("%d\n", val); exit(0); }
```

Benchmark results

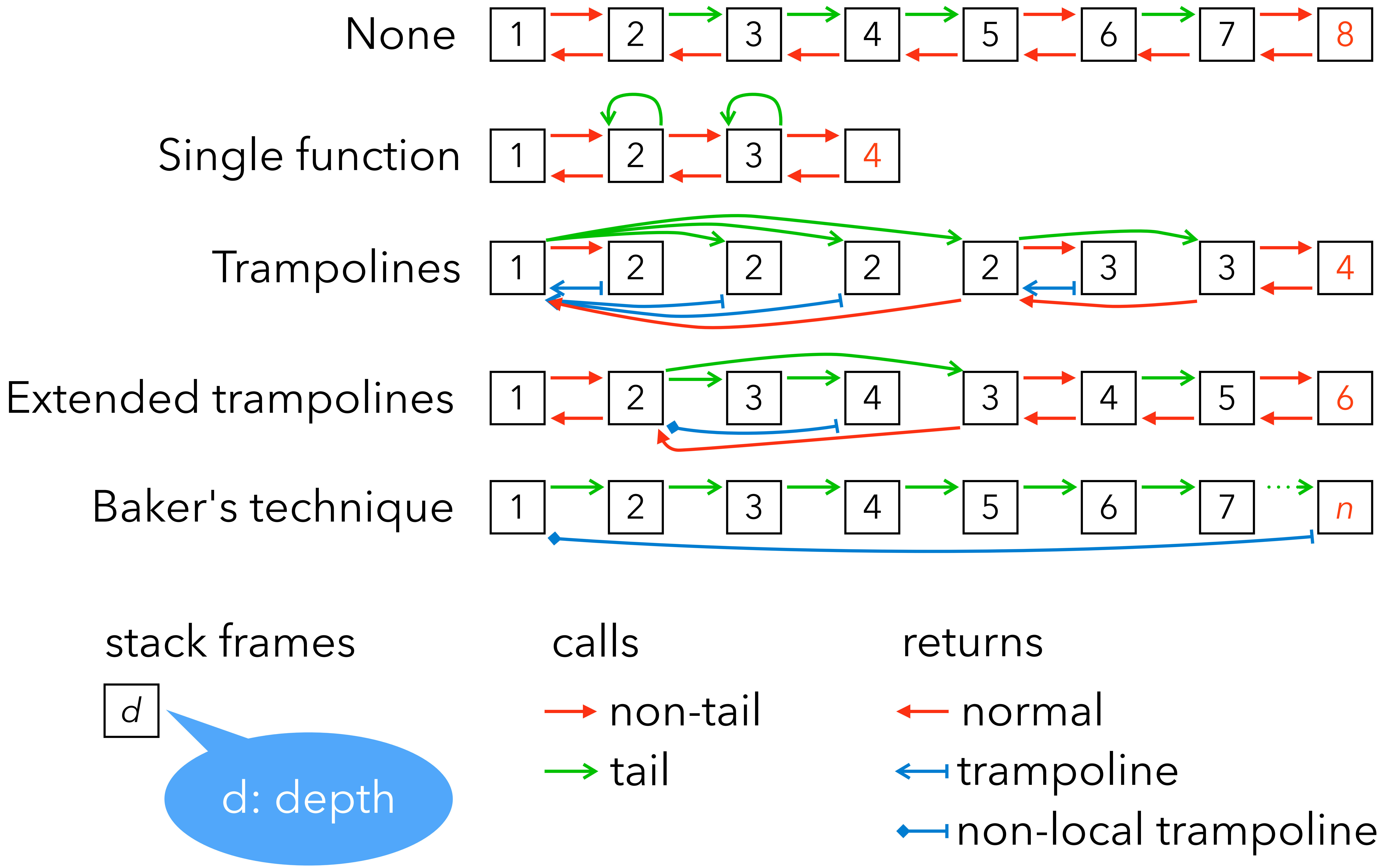
Processor: 2.3 GHz Intel Core i9

Compiler: clang 11.0.3

Optimization settings: `-O0` and `-O3`



Techniques summary



None

Single function

Trampolines

Extended trampolines

Baker's technique

stack frames

d

d: depth

calls

non-tail

tail

returns

normal

trampoline

non-local trampoline