Stack operation optimization in Pen

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Continuation Passing Style (CPS)

Direct style

```
f = \(x) {
  y = g()

  x + y
}
```

CPS

```
f = \(k, x) {
  g(\[k, x](y) {
    k(x + y)
  })
}
```

CPS for consecutive function calls

Direct style

```
f = \(x) {
  y = f()
  z = g()

  x + y + z
}
```

CPS

```
f = \(k, x) {
  f(\[k, x](y) {
    f(\[k, x, y](z) {
      k(x + y + z)
    })
  })
}
```

CPS in Pen

- Pen uses CPS to make all functions suspendable.
  - i.e. every function is an *async* function.
  - Functions are suspended for I/O, synchronization, etc.
- Pen doesn't support the first-class continuations.

CPS stack

- Pen uses two stacks at runtime.
- Machine stack
  - Nearly used other than reference count operations and foreign functions.
- Heap-allocated stack
  - Used to allocate "continuations" in CPS
  - No need for heap allocation of each continuation

CPS transformation

1. Calculate environments of continuations.
2. Compile a direct-style IR to ANF.
    - Using the second-class continuations
3. Compile Pen-native function calls into CPS.

Function entrypoints

```
fn function_entrypoint_2<A1, A2, T, F: Fn(A1, A2) -> T>(
    stack: &mut Stack,
    continuation: fn(stack: &mut Stack, result),
    closure: Arc<Closure<F>>,
    argument0: A0,
    argument1: A1,
) {
  // ...
}
```

- Continuations are raw function pointers of their entrypoints.
- Where are their environments?
    - In heap-allocated stacks!

Function calls

1. Create a continuation or pass it down from a caller.
2. **Push environment of a continuation to a stack if necessary.**
3. Call a function entrypoint with the continuation entrypoint.

Continuation entrypoint

1. **Pop environment of a continuation from a stack if necessary.**
2. Execute instructions.

What if those continuations' environments are the same or similar?

Examples

- In a continuation,
  - We pop free variables of `a`, `b`, `c`.
- In its continuation,
  - We push free variables of `b`, `c`.

In this case, we don't need to push the environment at all if stack elements are properly ordered.

In general, if stack elements of continuations in a function are ordered properly, we can calculate diff of those and generate codes only to fill the diff.

Stack operation optimization

- Stack elements are ordered by an ascending order of `2 ^ frequency`
  - `frequency` is a frequency at which free variables appear in continuations throughout a top-level function.
- When we push environments of continuations, we rather use partial push if applicable.
  i. Pop **all** unused free variables.
  ii. Push new free variables.

Result

- 5% size reduce in module object files
- CPU time performance improvement was pretty minimal (~1%.)

Questions

- Reinvention of the wheel?
  - Register coloring and active frame calculation?
  - `async` generator state machines in Rust
  - In CPS, we can extend and shrink active frames.
- Do we need minimum memory usage?
  - Tail call optimization + CPS = "stack GC"
  - Just use the maximum environment size throughout a function?
  - Is it more CPU-time friendly?

Summary

Stack operations are now fully optimized!

Appendix

Stack operations in CPS

In `Add`,

```
504: 42 00 00 91        add     x2, x2, #0
508: fd 7b 45 a9        ldp     x29, x30, [sp, #80]
50c: 29 01 08 8b        add     x9, x9, x8
510: 08 81 00 91        add     x8, x8, #32          <-
514: f6 57 43 a9        ldp     x22, x21, [sp, #48]
518: 28 29 01 6d        stp     d8, d10, [x9, #16]   <-
51c: 29 05 00 fd        str     d9, [x9, #8]         <-
520: 34 01 00 f9        str     x20, [x9]            <-
524: 68 06 00 f9        str     x8, [x19, #8]        <-
528: f4 4f 44 a9        ldp     x20, x19, [sp, #64]
```

At the beginning of `Add`'s first continuation,

```
2a70: ff 03 01 d1       sub     sp, sp, #64
2a74: 08 04 40 f9       ldr     x8, [x0, #8]                <-
2a78: 09 00 00 90       adrp    x9, 0x2000 <__k_1a+0x8>
2a7c: e9 23 01 6d       stp     d9, d8, [sp, #16]
2a80: 08 40 60 1e       fmov    d8, d0
2a84: f4 4f 02 a9       stp     x20, x19, [sp, #32]
2a88: f3 03 00 aa       mov     x19, x0
2a8c: 08 81 00 d1       sub     x8, x8, #32                 <-
2a90: fd 7b 03 a9       stp     x29, x30, [sp, #48]
2a94: 08 04 00 f9       str     x8, [x0, #8]                <-
2a98: 23 01 40 f9       ldr     x3, [x9]
```

At the end of `Add`'s first continuation,

```
2ae4: 42 00 00 91        add     x2, x2, #0
2ae8: fd 7b 43 a9        ldp     x29, x30, [sp, #48]
2aec: 08 81 00 91        add     x8, x8, #32           <-
2af0: 68 06 00 f9        str     x8, [x19, #8]         <-
2af4: 28 69 28 fc        str     d8, [x9, x8]          <-
2af8: 68 06 40 f9        ldr     x8, [x19, #8]         <-
2afc: e9 23 41 6d        ldp     d9, d8, [sp, #16]
2b00: 08 21 00 91        add     x8, x8, #8            <-
2b04: 68 06 00 f9        str     x8, [x19, #8]         <-
2b08: f4 4f 42 a9        ldp     x20, x19, [sp, #32]
```

```
        add     x10, x10, #8
        str     x8, [x0, #8]
Lloh21:
        ldr     x21, [x9, "_Foo.pen:f"@PAGEOFF+8]
        ldr     x9, [x0, #16]
        ldr     x0, [x0]
        cmp     x10, x9
        b.ls    LBB6_2
; %bb.1:                                ; %then.i
        lsl     x20, x9, #1
        mov     x1, x20
        bl      __pen_realloc
        ldr     x8, [x19, #8]
        str     x0, [x19]
        str     x20, [x19, #16]
LBB6_2:                                 ; %_fmm_stack_extend.exit
        add     x9, x8, #32
        add     x8, x0, x8
Lloh22:
        adrp    x1, __k_15@PAGE
Lloh23:
        add     x1, x1, __k_15@PAGEOFF
Lloh24:
        adrp    x2, "_Foo.pen:f"@PAGE+8
Lloh25:
        add     x2, x2, "_Foo.pen:f"@PAGEOFF+8
        str     x9, [x19, #8]
        mov     x0, x19
        str     d8, [x8, #32]
        ldr     x8, [x19, #8]
        add     x8, x8, #8
        str     x8, [x19, #8]
        blr     x21
        ldp     x29, x30, [sp, #48]             ; 16-byte Folded Reload
        ldp     x20, x19, [sp, #32]             ; 16-byte Folded Reload
        ldp     x22, x21, [sp, #16]             ; 16-byte Folded Reload
        ldp     d9, d8, [sp], #64               ; 16-byte Folded Reload
        ret
        .loh AdrpLdr    Lloh20, Lloh21
        .loh AdrpAdd    Lloh24, Lloh25
        .loh AdrpAdd    Lloh22, Lloh23
                                        ; -- End function
```

After:

```
        .p2align        2                               ; -- Begin function _k_1a
__k_1a:                                 ; @_k_1a
; %bb.0:                                ; %entry
        stp     d9, d8, [sp, #-64]!             ; 16-byte Folded Spill
        stp     x22, x21, [sp, #16]             ; 16-byte Folded Spill
        ldr     x22, [x0, #8]
Lloh20:
        adrp    x8, "_Foo.pen:f"@PAGE+8
        stp     x20, x19, [sp, #32]             ; 16-byte Folded Spill
        stp     x29, x30, [sp, #48]             ; 16-byte Folded Spill
        fmov    d8, d0
        sub     x9, x22, #32
        mov     x19, x0
        str     x9, [x0, #8]
        add     x9, x22, #8
Lloh21:
        ldr     x21, [x8, "_Foo.pen:f"@PAGEOFF+8]
        ldr     x8, [x0, #16]
        ldr     x0, [x0]
        cmp     x9, x8
```