

Continuations

Hype for Types

March 23, 2021

Exceptions

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fun fold f z nil = z
  | fold f z (x::xs) = f(x, fold f z xs)
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exception Ret
fun find' (p : 'a -> bool) (l : 'a list) : 'a option =
  fold
    (fn (x,_) => if p x then raise Ret x else NONE)
    NONE l
  handle Ret x => SOME x
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Prod

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fun fold f z nil = z
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fun prod p l =
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    op*
    1 l
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fun prod p l =
  fold
    op*
    1 l
```

```
fun prod p l =
  let exception Ret of int in
    fold
      (fn (0, _) => raise Ret 0 | (x, acc) => x * acc)
      1 l
    handle Ret i => i
  end
```


Continuations

CPS, but at the type level?

```
(* prod : int list -> (int -> 'a) -> 'a *)  
fun prod nil      k = k 1  
  | prod (0::_) k = k 0  
  | prod (x::xs) k = prod xs (fn res => k (x * res))
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Goal

Replace type `int -> 'a` with a *jump point* expecting an `int`.

Conveniently, SML <> SML/NJ

```
signature CONT =
sig
  type 'a cont
  val letcc : ('a cont -> 'a) -> 'a
  val throw : 'a cont -> 'a -> 'b
  val catch : ('a -> void) -> 'a cont
end

structure K :> CONT =
struct
  type 'a cont = 'a SMLofNJ.Cont.cont
  val letcc = SMLofNJ.Cont.callcc
  val throw = SMLofNJ.Cont.throw
  val catch = fn f => letcc (absurd o f o letcc o
    throw)
end
```

Some Rules

$$\frac{\Gamma, k : \tau \text{ cont} \vdash e : \tau}{\Gamma \vdash \text{letcc } k \text{ in } e : \tau}$$

$$\frac{\Gamma \vdash k : \tau \text{ cont} \quad \Gamma \vdash e : \tau}{\Gamma \vdash \text{throw } k \text{ } e : \tau'}$$

CPS, but at the type level!

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(* prod : int list -> int cont -> 'a *)  
fun prod nil      k = throw k 1  
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    (x * res)))
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  | prod (0::_) k = throw k 0  
  | prod (x::xs) k = prod xs (catch (fn res => throw k  
    (x * res)))  
  
- letcc (fn k => prod [1,2,3] k);  
val it = 6 : int
```

Example: values with holes

```
(* sum : int list -> (int, int * int cont) either *)  
(* sum [2, 1, 5] ==> INL 8 *)  
(* sum [2, ~2, 5] ==> INR (~2,K) *)
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```
type result = (int, int * int cont) either  
  
fun aux (L : int list) (k : result cont) : int =  
  case L of  
    nil => 0  
  | x::xs => letcc (fn here =>  
    if x < 0 then throw k (INR (x,here)) else x  
  ) + aux xs k  
  
val sum = fn L => letcc (fn k => INL (aux L k))
```

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fun sumNonneg L =  
  case sum L of  
    INL res => SOME res  
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```
fun positives L =  
  case sum L of  
    INL res      => res  
  | INR (n, k) => throw k (Int.abs n)
```

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local
  val readNum = fn () => valOf (Int.fromString (valOf(
    TextIO.inputLine TextIO.stdIn)))
in
  fun fromUser L =
    case sum L of
      INL res => res
    | INR (x, k) => (
        print ("We got: " ^ Int.toString x ^ " (?) ");
        throw k (readNum ())
      )
end
```

Back to Curry-Howard!

Is this Logical?

'a * 'b	$A \wedge B$
'a + 'b	$A \vee B$
'a -> 'b	$A \supset B$
unit	\top
void	\perp
'a cont	

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Programs are proofs...

Now $\neg A \triangleq 'a \text{ cont}$ instead of $\neg A \triangleq 'a \rightarrow \text{void}$.

Recall the helper `val catch : ('a -> void) -> 'a cont`

$$\neg(A \wedge \neg A)$$

$$\neg(A \vee B) \supset \neg A \wedge \neg B$$

$$(A \supset B) \supset \neg(A \wedge \neg B)$$

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fn k => (catch (throw k o INL)
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$\neg(A \vee B) \supset \neg A \wedge \neg B$	<code>fn k => (catch (throw k o INL) ,catch (throw k o INR))</code>
-----------------------------------------------	--------------------------------------------------------------------------------------

$(A \supset B) \supset \neg(A \wedge \neg B)$	<code>fn f => catch (fn (a,nb) => throw nb (f a))</code>
-----------------------------------------------	------------------------------------------------------------------------------------

Finally a proof of $A \vee \neg A$

Let P be “there exists a word ending with the letter e.”

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Proof.

There are no such words. □

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We prove $P \vee \neg P$ by proving P .

Proof.

There is such a word.

Finally a proof of $A \vee \neg A$

Let A be “there exists a word ending with the letter e.”

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There is such a word. It's “grape”.



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Important Idea

Continuations correspond to *classical logic*!

Classical Proofs!?

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We'll provide the helper `val catch : ('a -> void) -> 'a cont`¹

$$A \vee \neg A$$

$$\neg(A \wedge B) \supset \neg A \vee \neg B$$

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¹`val catch = letcc (absurd o f o letcc o throw)`

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fn nab => letcc (fn k =>
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```
fn k => fn a =>
  letcc (fn nb => throw k (a,nb))
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¹`val catch = letcc (absurd o f o letcc o throw)`

What the hype?!

Claim: $\exists a, b \in \mathbb{R}. \neg a \text{ rational} \wedge \neg b \text{ rational} \wedge a^b \text{ rational}$

Proof.

Case on $\sqrt{2}^{\sqrt{2}}$ rational $\vee \neg \sqrt{2}^{\sqrt{2}}$ rational.

Case 1. Let $a = \sqrt{2}$ and $b = \sqrt{2}$.

Case 2. Let $a = \sqrt{2}^{\sqrt{2}}$ and $b = \sqrt{2}$.



Remember how LEM works! It asserts that it's false... until you prove it wrong.

Demo: True or Not True?

```
val weird = fn () =>
  let
    val p = K.letcc (fn na => INR (K.catch (K.throw na
      o INL))) : (unit, unit K.cont) Either.either
  in
    case p of
      INL () => print "duh, true is true\n"
    | INR k  => (print "uhhh what?\n"; K.throw k ())
  end
```

Conclusion

- Continuations are useful to program with! They let you alter control flow.

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- Classical logic doesn't hold much proof content.