

Continuations in Haskell

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What we are going to cover today

- ▶ The basics of CPS style
- ▶ The **Cont** monad
- ▶ Call with Current Continuation (**callCC**)
- ▶ An motivating use case

The Basics of CPS Style

How do we compute things?

Computing a value is normally quite simple.

```
type Radius = Double
```

```
type Area = Double
```

```
areaCircle :: Radius → Area
```

```
areaCircle r = pi * r * r
```

```
areaCircle 1 =  $\pi$ 
```

How do we compute things?

Computing a value is normally quite simple.

```
type Radius = Double  
type Area = Double
```

```
areaCircle :: Radius → Area  
areaCircle r = pi * r * r
```

```
areaCircle 1 —  $\pi$ 
```

But what if we have some value (radius/width/etc), but we don't know what area function to use yet.

How do we make a value wait for a function?

Normally we have a function wait for a value.

$(\$)$:: $(a \rightarrow b) \rightarrow a \rightarrow b$
 f \$ $x = f\ x$

How do we make a value wait for a function?

Normally we have a function wait for a value.

```
($) :: (a → b) → a → b  
f $ x = f x
```

What if we flip the arguments?

```
(£) :: a → (a → b) → b  
(£) = flip ($)  
— or (£) = \x → (\f → f x)
```

Now we can do all sorts of things to the same radius

```
type Height = Double; type Volume = Double; type Diameter = Double
```

```
volumeCylinder :: Radius → Height → Volume
```

```
volumeCylinder r h = areaCircle r * h
```

```
diameter :: Radius → Diameter
```

```
diameter r = 2*r
```

```
doSomethingToR :: (Radius → r) → r
```

```
doSomethingToR = (1.0 £)
```


Now we can do all sorts of things to the same radius

```
type Height = Double; type Volume = Double; type Diameter = Double
```

```
volumeCylinder :: Radius → Height → Volume
```

```
volumeCylinder r h = areaCircle r * h
```

```
diameter :: Radius → Diameter
```

```
diameter r = 2*r
```

```
doSomethingToR :: (Radius → r) → r
```

```
doSomethingToR = (1.0 £)
```

```
doSomethingToR areaCircle —  $\pi$ 
```

```
— doSomethingToR volumeCylinder :: Height → Volume
```

```
doSomethingToR volumeCylinder 2 —  $2\pi$ 
```

```
doSomethingToR diameter — 2
```

Suspended computation

`£` creates what is known as a suspended computation.

`areaCircle` — **Waiting for an input**

Suspended computation

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`areaCircle` — Waiting for an input

`areaCircle 1` — Represents a value

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`(areaCircle 1 £)` — Wait to do something with the
— result of `areaCircle 1`

Suspended computation

`£` creates what is known as a suspended computation.

`areaCircle` — Waiting for an input

`areaCircle 1` — Represents a value

`(1 £)` — Do something to the value 1 later

`(areaCircle 1 £)` — Wait to do something with the
— result of `areaCircle 1`

`areaCircle 1 £ id` — Execute 'areaCircle 1',
— pass the result to `id`

Standard Notation for Suspended Computations

In the literature/online, you will likely see turning a value into a suspended computation written as follows.

`cpsify :: a → (a → r) → r`

`cpsify x k = k x`

— or `cpsify x = \k → k x`

where

- ▶ `r` is the final result of evaluating the computation.
- ▶ `a → r` is what you are doing to do to `x` later. This is represented here as `k`.
- ▶ `k` is also called the “continuation”, or “continue on with the value you pass to me”.

Currently we can't do much

We can create suspended computations quite easily using **cpsify**.
What we really need is something to *chain* our suspended computations together.

Chaining Training Wheels

Say we have two suspended computations.

```
suspendArea :: Radius → (Area → r) → r  
suspendArea r = \k → k (areaCircle r)
```

— Calculate the volume of any extrusion.

```
suspendExtrude :: Area → Height → (Volume → r) → r  
suspendExtrude a h = \k → k (a * h)
```

Chaining Training Wheels

Say we have two suspended computations.

```
suspendArea :: Radius → (Area → r) → r  
suspendArea r = \k → k (areaCircle r)
```

— Calculate the volume of any extrusion.

```
suspendExtrude :: Area → Height → (Volume → r) → r  
suspendExtrude a h = \k → k (a * h)
```

What we would like is something like this

```
suspendVolume :: Radius → Height → (Volume → r) → r
```

Chaining Training Wheels

We could try this.

```
suspendVolume :: Radius → Height → (Volume → r) → r  
suspendVolume r h = \k → ?    — k :: (Volume → r) → r
```

Chaining Training Wheels

We could try this.

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    suspendArea r              — needs a (Area → r)
```

Chaining Training Wheels

We could try this.

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    suspendArea r              — needs a (Area → r)
    (\area → ?)                — needs to return r
```

Chaining Training Wheels

We could try this.

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    suspendArea r              — needs a (Area → r)
    (\area →                   — needs to return r
        suspendExtrude area h ?) — needs a (Volume → r)
```

Chaining Training Wheels

We could try this.

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
  suspendArea r              — needs a (Area → r)
  (\area →                  — needs to return r
    suspendExtrude area h    — needs a (Volume → r)
    k)                       — k is a (Volume → r)!
```

suspendVolume seems to work

We get a suspended computation that calculates the volume and waits for us to do something with it.

```
suspendVolume 1 2      — :: (Volume → r) → r  
suspendVolume 1 2 id   —  $2\pi$   
suspendVolume 1 2 (*2) —  $2 * 2\pi = 4\pi$ 
```

Let's break it down to make sure we are calculating what we want.

Breakdown suspendVolume

- `suspendArea r = \k → k (areaCircle r)`
- `suspendExtrude a h = \k → k (a * h)`

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    (suspendArea r)           — needs a (Area → r)
    (\area →                  — needs to return r
      (suspendExtrude area h) — needs a (Volume → r)
      k)                      — k is a (Volume → r)!
```

Expand `suspendArea`.

Breakdown suspendVolume

- `suspendArea r = \k → k (areaCircle r)`
- `suspendExtrude a h = \k → k (a * h)`

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
  (\k → k (areaCircle r)      — needs a (Area → r)
  (\area →                    — needs to return r
    (suspendExtrude area h)   — needs a (Volume → r)
    k)                        — k is a (Volume → r)!
```

Evaluate the `(\k → k (areaCircle r))`.

Breakdown suspendVolume

- `suspendArea r = \k → k (areaCircle r)`
- `suspendExtrude a h = \k → k (a * h)`

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    (\area →                  — needs to return r
      (suspendExtrude area h)  — needs a (Volume → r)
      k)                       — k is a (Volume → r)!
    (areaCircle r)            — areaCircle applied to
                                — \area → ...
```

Substitute in `area`.

Breakdown suspendVolume

- `suspendArea r = \k → k (areaCircle r)`
- `suspendExtrude a h = \k → k (a * h)`

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    (suspendExtrude (areaCircle r) h) — needs (Volume → r)
    k                                — k is a (Volume → r)!
```

Expand `suspendExtrude`.

Breakdown suspendVolume

- `suspendArea r = \k → k (areaCircle r)`
- `suspendExtrude a h = \k → k (a * h)`

```
suspendVolume :: Radius → Height → (Volume → r) → r
suspendVolume r h = \k →      — k :: (Volume → r) → r
    (\k → k $ (areaCircle r) * h) — needs (Volume → r)
    k)                          — k is a (Volume → r)!
```

Apply k.

Breakdown suspendVolume

- `suspendArea r = \k → k (areaCircle r)`
- `suspendExtrude a h = \k → k (a * h)`

```
suspendVolume' :: Radius → Height → (Volume → r) → r
suspendVolume' r h = \k →      — k :: (Volume → r) → r
    k $ areaCircle r * h
```

Well that is certainly correct!

Manual chaining is suspended rear pain

We can do better. We have a common pattern here


```
suspendA :: (a → r) → r
```

```
suspendB :: a → (b → r) → r
```

```
suspendA (\a → (suspendB a) (\b → ...))
```

Let's turn this pattern into a function¹

```
chain :: ((a → r) → r) → (a → ((b → r) → r)) →  
        ((b → r) → r)
```

¹From The Haskell Wikibook, although there it is called `chainCPS` 

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We can do better. We have a common pattern here

```
suspendA :: (a → r) → r  
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suspendA (\a → (suspendB a) (\b → ...))
```

Let's turn this pattern into a function¹

```
chain :: ((a → r) → r) → (a → ((b → r) → r)) →  
        ((b → r) → r)
```

```
chain sA aToSB = \k → — k :: (b → r)  
    sA                — needs a (a → r)  
    (\a →  
        aToSB a        — needs a (b → r)  
        k)              — k is a (b → r)!
```

¹From The Haskell Wikibook, although there it is called `chainCPS` 

Making `suspendVolume` is much easier now

— `suspendArea r = \k → k (areaCircle r)`

— Flip arguments to chain easier.

`suspendExtrude' :: Height → Area → (Volume → r) → r`

`suspendExtrude' h a = suspendExtrude a h`

`suspendVolume'' :: Radius → Height → (Volume → r) → r`

`suspendVolume'' r h = suspendArea r 'chain'`
`suspendExtrude' h`

— `chain` for us looks like

`chain :: ((Area → r) → r) → (Area → ((Volume → r) → r)) →`
`((Volume → r) → r)`

I smell a monadic burrito (link)

`cpsify` (or `(£)`) is acting like `return`, and `chain` is acting like `bind` (`(>=)`). Lets make a type for these suspended computations then.

— Already defined in `Control.Monad.Trans.Cont`

```
newtype Cont r a = Cont {runCont :: (a → r) → r}
```

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`cpsify` (or `(£)`) is acting like `return`, and `chain` is acting like `bind` (`(>=)`). Lets make a type for these suspended computations then.

— Already defined in `Control.Monad.Trans.Cont`

```
newtype Cont r a = Cont {runCont :: (a → r) → r}
```

```
instance Monad (Cont r) where
```

```
    return :: a → Cont r a
```

```
    return x = Cont (\k → k x)
```

```
    — cpsify x =      \k → k x
```

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`cpsify` (or `(£)`) is acting like `return`, and `chain` is acting like `bind` (`(>=)`). Lets make a type for these suspended computations then.

— Already defined in `Control.Monad.Trans.Cont`

```
newtype Cont r a = Cont {runCont :: (a → r) → r}
```

```
instance Monad (Cont r) where
```

```
    return :: a → Cont r a
```

```
    return x = Cont (\k → k x)
```

```
    — cpsify x =      \k → k x
```

```
    (>=) :: Cont r a → (a → Cont r b) → Cont r b
```

```
    m >= f = Cont
```

```
        (\k → runCont m (\a → runCont (f a) k))
```

```
    — chain m f = \k → m (\a →      (f a) k)
```

The **Cont** monad

do sweetness is now possible

Cont is a monad, which means we can get some nice **do** syntactic sugar.

— `Control.Monad.Trans.Cont` exports `cont`, not `Cont`
`cont = Cont`

```
suspendAreaCont :: Radius → Cont r Area  
suspendAreaCont r = cont (\k → k (areaCircle r))
```

```
suspendExtrudeCont :: Height → Area → Cont r Volume  
suspendExtrudeCont h a = cont (\k → k (a * h))
```

```
suspendVolumeCont :: Radius → Height → Cont r Volume  
suspendVolumeCont r h = do  
  area ← suspendAreaCont r  
  suspendExtrudeCont h area
```

What happens if we forget the k?

The **k** in the prior functions represented “the rest of the computation”. So what happens when we forget the k?

— I wonder where the **r** went....

```
suspendAreaOps :: Double → Cont Double Double
```

```
suspendAreaOps r = cont (\_ → areaCircle r)
```

```
suspendVolumeOps :: Radius → Height → Cont Double Double
```

```
suspendVolumeOps r h = do
```

```
  area ← suspendAreaOps r
```

```
  suspendExtrudeCont h area
```

What is the result of the following?

```
oops :: Double
```

```
oops = runCont (suspendVolumeOps 1 2) id
```

What happens if we forget the k?

The **k** in the prior functions represented “the rest of the computation”. So what happens when we forget the **k**?

— I wonder where the **r** went....

```
suspendAreaOps :: Double → Cont Double Double
```

```
suspendAreaOps r = cont (\_ → areaCircle r)
```

```
suspendVolumeOps :: Radius → Height → Cont Double Double
```

```
suspendVolumeOps r h = do
```

```
  area ← suspendAreaOps r
```

```
  suspendExtrudeCont h area
```

What is the result of the following?

```
oops :: Double
```

```
oops = runCont (suspendVolumeOps 1 2) id
```

— `oops == π`

— (wait, that is not $(\pi * 1^2) * 2 = 2 * \pi$)

The `k` meant “keep going!”

Normally we have this kind of scenario.

`area` \rightarrow `extrude` \rightarrow `suspended computation`

— or `(area` \rightarrow `((extrude` \rightarrow `suspended computation))`

— `k` is “conceptually” \wedge ————— \wedge

When we did not call `k`, we forgot to keep going forward and instead did this.

`area` \rightarrow `suspended computation`

What happens if we double the use of k?

```
suspendAreaDb1 :: Radius → Cont [r] Area  
suspendAreaDb1 r = cont (\k → k (areaCircle r) ++  
                           k (areaCircle (r + 2)))
```

```
suspendVolumeDb1 :: Radius → Height → Cont [r] Volume  
suspendVolumeDb1 r h = do  
  area ← suspendAreaDb1 r  
  suspendExtrudeCont h area
```

What is the result of the following?

```
dbl :: [Volume]  
dbl = runCont (suspendVolumeDb1 1 2) return
```

What happens if we double the use of k?

```
suspendAreaDb1 :: Radius → Cont [r] Area
suspendAreaDb1 r = cont (\k → k (areaCircle r) ++
                             k (areaCircle (r + 2)))
```

```
suspendVolumeDb1 :: Radius → Height → Cont [r] Volume
suspendVolumeDb1 r h = do
  area ← suspendAreaDb1 r
  suspendExtrudeCont h area
```

What is the result of the following?

```
dbl :: [Volume]
dbl = runCont (suspendVolumeDb1 1 2) return
```

— `dbl = [6.283185307179586, 56.548667764616276]`
— `dbl = [2π] ++ [18π]`

We execute the remaining computation twice, and throw the result into `\k → k (areaCircle r) ++ k (areaCircle (r + 2))`

What do we currently have?

We have a few tools to make suspended computations.

- ▶ A way to create suspended computations (**cpsify** or **return**)
- ▶ A way to chain those computations (**chain** or **(>=)**)
- ▶ All of this wrapped in a type **Cont r a**

In addition, we have seen how to break out of the standard control flow.

- ▶ Forget **k**: do not process any more lines in the continuation.
- ▶ Use **k** twice: repeat the continuation twice, combine results.

Call with Current Continuation (**callCC**)

What else could we want?

- ▶ We have a way to stop what we were doing (forget **k**)
- ▶ We have a way to “branch” (use **k**) twice
- ▶ We didn’t talk about it but if **k :: (r → r)** then we can run a function on itself again ($\backslash k \rightarrow k (k (...))$)

Once we are in **Cont**, using **k** is somewhat tedious (it needs to be explicitly brought out).

An eject button would be nice

What if we brought out **k** only when we needed it? Where **k** is “skip whatever else we were going to do in this continuation and keep going with the next one”.

Ejecting with `callCC`

There is a function that does this called “call with current continuation”, or `callCC` in Haskell.

```
callCC :: ((a -> Cont r b) -> Cont r a) -> Cont r a
```

```
calc :: Double -> Double -> String
```

```
calc a b = ('runCont' id) $ do
```

```
  ans <- callCC $ \eject -> do
```

```
    c <- return $ a*2 + b + 3
```

```
    when (c == 0) (eject "oops dividing by 0")
```

```
    d <- return $ a + b
```

```
    return $ show (d / c)
```

```
  return $ "Answer: " ++ ans
```


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```
callCC :: ((a → Cont r b) → Cont r a) → Cont r a
```

```
calc :: Double → Double → String
```

```
calc a b = ('runCont' id) $ do
```

```
  — |— Calling 'eject' is the same as
```

```
  — v   'ans ← return "oops dividing by 0"
```

```
ans ← callCC $ \eject → do
```

```
  c ← return $ a*2 + b + 3
```

```
  when (c == 0) (eject "oops dividing by 0")
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return $ "Answer: " ++ ans
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Ejecting with `callCC`

There is a function that does this called “call with current continuation”, or `callCC` in Haskell.

```
callCC :: ((a → Cont r b) → Cont r a) → Cont r a
```

```
calc :: Double → Double → String
```

```
calc a b = ('runCont' id) $ do
```

- |— ‘eject’ is often called ‘k’; ‘k’ is the same as
- v ‘ans ← return "oops dividing by 0"’

```
ans ← callCC $ \k → do
```

```
  c ← return $ a*2 + b + 3
```

```
  — k :: String → Cont String ()
```

```
  when (c == 0) (k "oops dividing by 0")
```

```
  d ← return $ a + b
```

```
  — String → Cont String String
```

```
  return $ show (d / c)
```

```
return $ "Answer: " ++ ans
```

Guess the answers

What happens when we call `calc`

```
calc :: Double → Double → String
```

```
calc a b = ('runCont' id) $ do
```

```
  ans ← callCC $ \k → do
```

```
    c ← return $ a*2 + b + 3
```

```
    when (c == 0) (k "oops dividing by 0")
```

```
    d ← return $ a + b
```

```
    return $ show (d / c)
```

```
  return $ "Answer: " ++ ans
```

```
calc_1 = calc 1 2    — ?
```

Guess the answers

What happens when we call `calc`

```
calc :: Double → Double → String
```

```
calc a b = ('runCont' id) $ do
```

```
  ans ← callCC $ \k → do
```

```
    c ← return $ a*2 + b + 3
```

```
    when (c == 0) (k "oops dividing by 0")
```

```
    d ← return $ a + b
```

```
    return $ show (d / c)
```

```
  return $ "Answer: " ++ ans
```

```
calc_1 = calc 1 2    — "Answer: 0.42857142857142855"
```

Guess the answers

What happens when we call `calc`

```
calc :: Double → Double → String
```

```
calc a b = ('runCont' id) $ do
```

```
  ans ← callCC $ \k → do
```

```
    c ← return $ a*2 + b + 3
```

```
    when (c == 0) (k "oops dividing by 0")
```

```
    d ← return $ a + b
```

```
    return $ show (d / c)
```

```
  return $ "Answer: " ++ ans
```

```
calc_1 = calc 1 2    — "Answer: 0.42857142857142855"
```

```
calc_2 = calc 0 (-3) — ?
```

Guess the answers

What happens when we call `calc`

```
calc :: Double → Double → String
```

```
calc a b = ('runCont' id) $ do
```

```
  ans ← callCC $ \k → do
```

```
    c ← return $ a*2 + b + 3
```

```
    when (c == 0) (k "oops dividing by 0")
```

```
    d ← return $ a + b
```

```
    return $ show (d / c)
```

```
  return $ "Answer: " ++ ans
```

```
calc1 :: String
```

```
calc1 = calc 1 2    — "Answer: 0.42857142857142855"
```

```
calc2 :: String
```

```
calc2 = calc 0 (-3) — "Answer: oops dividing by 0"
```

Passing k around

Shortcutting is useful when we realize that *there is nothing more to do*. For example, the product of a list containing **0** is **0**.²

```
prod :: (Eq a, Num a) => [a] -> a
prod l = ('runCont' id) $ callCC (\k -> loop k l)
  where
    loop _ []      = return 1
    loop k (0:_)   = k 0
    loop k (x:xs) = do
      n <- loop k xs
      return (n*x)
```

²From the Haskell Wiki `delcont` page

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      n <- loop k xs
      return (n*x)
```

```
prod [1, 2, 3, 4]    — ?
```

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Shortcutting is useful when we realize that *there is nothing more to do*. For example, the product of a list containing **0** is **0**.⁴

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    loop k (x:xs) = do
      n <- loop k xs
      return (n*x)
```

```
prod [1, 2, 3, 4]    — 24
```

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Shortcutting is useful when we realize that *there is nothing more to do*. For example, the product of a list containing 0 is 0.⁵

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    loop k (x:xs) = do
      n <- loop k xs
      return (n*x)
```

```
prod [1, 2, 3, 4]    — 24
prod [1, 2, 0, 3, 4] — ?
```

⁵From the Haskell Wiki `delcont` page

Passing k around

Shortcutting is useful when we realize that *there is nothing more to do*. For example, the product of a list containing 0 is 0.⁶

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    loop k (x:xs) = do
      n <- loop k xs
      return (n*x)
```

```
prod [1, 2, 3, 4]    — 24
prod [1, 2, 0, 3, 4] — 0 by shortcut
```

⁶From the Haskell Wiki `delcont` page

What we have done so far

- ▶ We have a way to stop what we were doing (forget **k**)
- ▶ We have a way to “branch” (use **k**) twice
- ▶ We didn’t talk about it but if **k :: (r → r)** then we can run a function on itself again (**\k → k (k (...))**)
- ▶ We can eject from a function (**callCC**)

What you can build with continuations

Lots of different control structures, including

- ▶ Exceptions
- ▶ Coroutines
- ▶ Generators/Iterators

Thanks

References I

All bullets are clockable links.

Tutorials

- ▶ [The Mother of all Monads](#)
- ▶ [Continuation Passing Style: Haskell Wikibooks](#)
- ▶ [Continuations in Haskell](#)
- ▶ [Haskell for All: The Continuation Monad \(on modular development using continuations and sum types\)](#)
- ▶ [Understanding Continuations \(this one can be a bit tricky for new Haskell users\).](#)
- ▶ [Understanding the callCC example in above](#)

CallCC

- ▶ [call/cc implementation StackOverflow](#)
- ▶ [Example callCC usage \(in Scheme\)](#)

References II

- ▶ callCC patterns (in Scheme)

Real World Use

- ▶ CPS is great! CPS is terrible! (on the use in attoparsec)

Delimited Continuations

- ▶ Delimited Continuations in Haskell tutorial
- ▶ Example code for delimited continuations in haskell
- ▶ Library CC-delcont examples
- ▶ Delimited Continuations and co-monads video

Extra Code

Set Example

We can define sets as a list with a careful insertion function.

```
newtype Set a = Set {getSet :: [a]} deriving (Show)
```

```
empty :: Set a  
empty = Set []
```

```
insert :: Eq a => Set a -> a -> Set a  
insert (Set []) x = Set [x]  
insert s@(Set (y:ys)) x = if x == y  
    then s  
    else Set $ y : getSet (insert (Set ys) x)
```

What is problematic when **insert** is given a value already in the set?

(Modified problem from Okasaki's "Purely Functional Data Structures", problem 2.3)

insert allocates unneeded nodes

Given a set s .

$s = a : b : c : d : e : f : []$


insert allocates unneeded nodes

Given a set `s`.

```
s = a : b : c : d : e : f : []
```



```
insert s d = a : b : c : |
```



`insert` allocates a (mostly) new `Set`.

A “smarter” insert

Let's use a continuation to return `s` when `x` is in `s`.

```
insert' :: Eq a => Set a -> a -> Set a
insert' s' x = ('runCont' id) $ callCC (\k -> insertShortcut k s')
  where
    insertShortcut _ (Set [])      = return $ Set [x]
    insertShortcut k (Set (y:ys)) =
      if x == y
      then k s'
      else insertShortcut k => setcons y $ Set ys

    setcons y (Set ys) = return $ Set (y : ys)
```

`insert'` uses less memory

Given a set `s`.

`s = a : b : c : d : e : f : []`
 \wedge ----- \wedge

`insert' s d =` |

`insert'` returns the same `s` if an element `x` is in `s`.

```
{-----  
- Testing with IO -  
-----}
```

```
io1 :: Int → ContT () IO String
```

```
io1 x = ContT $ \k → do  
    putStrLn "io1 start"  
    k $ show x  
    putStrLn "io1 end"
```

```
io2 :: String → ContT () IO String
```

```
io2 s = ContT $ \k → do  
    putStrLn "io2 start"  
    k (s ++ " io2")  
    putStrLn "io2 end"
```

```
ioExample :: Int → ContT () IO String
```

```
ioExample = io1 ➡ io2
```

From the “Understanding Continuations” FP article.

```
fpExample :: IO ()
fpExample = flip runContT return $ do
  lift $ putStrLn "alpha"
  (k, num) <- callCC $ \k -> let f x = k (f, x)
                                in return (f, 0 :: Integer)
  lift $ putStrLn "beta"           — k
  lift $ putStrLn "gamma"         — j
  if num < 5
    then void (k (num + 1))
    else lift $ print num          — 1
```