

The Worker/Wrapper Transformation

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The Worker/Wrapper Transformation

The Worker/Wrapper Transformation is a rewrite technique which changes the type of a (recursive) computation

- Worker/wrapper has been used inside the Glasgow Haskell compiler since its inception to rewriting functions that use lifted values (thunks) into equivalent and more efficient functions that use unlifted values.
- This talk will explain **why** worker/wrapper works!
- Much, much more general than just exploiting strictness analysis
- Worker/wrapper is about changing types

Changing the type of a computation . . .

- is pervasive in functional programming
- useful in practice
- the essence of turning a specification into an implementation

Thesis:

- The Worker/Wrapper Transformation is a great technique for changing types

This talk

- Examples of **what** worker/wrapper can do
- Formalize the Worker/Wrapper Transformation (**why** it works)
- Give a recipe for its use
- Show **how** to apply our worker/wrapper recipe to some examples

Example 1: Strictness Exploitation

Before

```
fac :: Int -> Int -> Int
fac n m = if n == 1
          then m
          else fac (n - 1) (m * n)
```

- n is trivially strict, m is provably strict
- Can use $Int\#$, a strict version of Int that is passed by value for n and m

After

```
fac n m = box (work (unbox n) (unbox m))

work :: Int# -> Int# -> Int#
work n# m# = if n# ==# 1#
              then m#
              else work (n# -# 1#) (m# *# n#)
```

Example 2: Avoiding Needless Deconstruction

Before

```
last      :: [a] -> a
last []   = error "last: []"
last (x:[]) = x
last (x:xs) = last xs
```

- The recursive call of `last` never happens with an empty list
- Subsequent recursive invocations performs a needless check for an empty list

After

```
last []      = error "last: []"
last (x:xs) = work x xs

work :: a -> [a] -> a
work x []    = x
work x (y:ys) = work y ys
```

Example 3: Efficient nub

Before

```
nub :: [Int] -> [Int]
nub [] = []
nub (x:xs) = x : nub (filter (\y -> not (x == y)) xs)
```

- filter is applied to the tail of the argument list on each recursive call, to avoid duplication
- It would be more efficient to remember the elements that have already been issued

After

```
nub :: [Int] -> [Int]
nub xs = work xs empty

work :: [Int] -> Set Int -> [Int]
work xs except =
  case dropWhile (\ x -> x `member` except) xs of
    [] -> []
    (x:xs) -> x : work xs (insert x except)
```

Example 4: Memoization

Before

```
fib :: Nat -> Nat
fib n = if n < 2 then 1 else fib (n-1) + fib (n-2)
```

- Memoization is a well-known optimization for `fib`
- Memoization is just a change in representation over the recursive call

After

```
fib :: Nat -> Nat
fib n = work !! n

work :: [Nat]
work = map f [0..]
  where f = if n < 2 then 1 else work !! (n-1) + work !! (n-2)
```

Example 5: Double-barreled CPS Translation

Before

```
eval :: Expr -> Maybe Int
eval (Val n)      = Just n
eval (Add x y)    = case eval x of Nothing -> Nothing
                    Just n   -> case eval y of Nothing -> Nothing
                                   Just m   -> Just (n+m)

eval (Throw)      = Nothing
eval (Catch x y)  = case eval x of Nothing -> eval y
                    Just n   -> Just n
```

- CPS changes the result type from A to $(A \rightarrow X) \rightarrow X$
- Again, just a change in representation

After

```
eval e = work e Just Nothing
```

```
work :: Expr -> (Int -> Maybe Int) -> Maybe Int -> Maybe Int
work (Val n)      s f = s n
work (Add x y)    s f = work x (\n -> work y (\m -> s (n+m)) f) f
work (Throw)      s f = f
work (Catch x y)  s f = work x s (work y s f)
```

Changing the *representation* of a computation ...

- is pervasive in functional programming
- useful in practice
- the essence of turning a specification into an implementation
- is what worker/wrapper does

Creating Workers and Wrappers for last

```
last :: [a] -> a
last =
```

```
\ v -> case v of
    []      -> error "last: []"
  (x:xs) -> case xs of
    []      -> x
    (_:_)  -> last xs
```

Creating Workers and Wrappers for last

```
last :: [a] -> a
last =
```

```
last_work :: a -> [a] -> a
last_work = \ x xs ->
  (\ v -> case v of
    []      -> error "last: []"
    (x:xs) -> case xs of
      []      -> x
      (_:_)  -> last xs) (x:xs)
```

- Create the worker out of the body and an invented coercion to the target type

Creating Workers and Wrappers for last

```
last :: [a] -> a
```

```
last = \ v -> case v of  
    []      -> error "last: []"  
    (x:xs) -> last_work x xs
```

```
last_work :: a -> [a] -> a
```

```
last_work = \ x xs ->  
    (\ v -> case v of  
        []      -> error "last: []"  
        (x:xs) -> case xs of  
            []      -> x  
            (_:_) -> last xs) (x:xs)
```

- Create the worker out of the body and an invented coercion to the target type
- Invent the wrapper which call the worker

Creating Workers and Wrappers for last

```
last :: [a] -> a
```

```
last = \ v -> case v of  
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    (x:xs) -> last_work x xs
```

```
last_work :: a -> [a] -> a
```

```
last_work = \ x xs ->  
    (\ v -> case v of  
        []      -> error "last: []"  
        (x:xs) -> case xs of  
            []      -> x  
            (_:_) -> last xs) (x:xs)
```

- Create the worker out of the body and an invented coercion to the target type
- Invent the wrapper which call the worker
- **These functions are mutually recursive**

Inline Wrapper

```
last :: [a] -> a
last = \ v -> case v of
    []      -> error "last: []"
    (x:xs) -> last_work x xs

last_work :: a -> [a] -> a
last_work = \ x xs ->
    (\ v -> case v of
        []      -> error "last: []"
        (x:xs) -> case xs of
            []      -> x
            (_:_) -> last xs) (x:xs)
```

- We now inline `last` inside `last_work`

Inline Wrapper

```
last :: [a] -> a
last = \ v -> case v of
    []      -> error "last: []"
    (x:xs) -> last_work x xs
```

```
last_work :: a -> [a] -> a
last_work = \ x xs ->
    (\ v -> case v of
        []      -> error "last: []"
        (x:xs) -> case xs of
            []      -> x
            (_:_) ->
                (\ v -> case v of
                    []      -> error "last: []"
                    (x:xs) -> last_work x xs) xs) (x:xs)
```

- We now inline last inside last_work
- last_work is now trivially recursive.

Simplify work

```
last :: [a] -> a
last = \ v -> case v of
    []      -> error "last: []"
    (x:xs) -> last_work x xs
```

```
last_work :: a -> [a] -> a
last_work = \ x xs ->
    (\ v -> case v of
        []      -> error "last: []"
        (x:xs) -> case xs of
            []      -> x
            (_:_) ->
                (\ v -> case v of
                    []      -> error "last: []"
                    (x:xs) -> last_work x xs) xs) (x:xs)
```

- We now simplify the worker

Simplify work

```
last :: [a] -> a
last = \ v -> case v of
    []      -> error "last: []"
    (x:xs) -> last_work x xs
```

```
last_work :: a -> [a] -> a
last_work = \ x xs ->
```

```
    case xs of
        []      -> x
        (x:xs) -> last_work x xs
```

- We now simplify the worker
- Reaching our efficient implementation

The Informal Worker Wrapper Methodology

- From a recursive function, construct two new functions

Wrapper

- Replacing the original function
- Coerces call to Worker

Worker

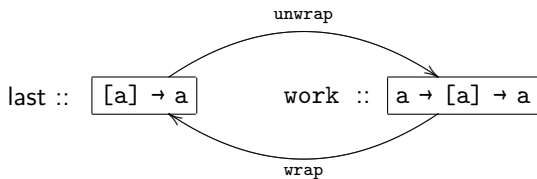
- Performs main computation
- Syntactically contains the body of the original function
- Coerces call from Wrapper

- The initial worker and wrapper are mutually recursive
- We then inline the wrapper inside the worker, and simplify
- We end up with
 - An efficient recursive worker
 - An impedance matching non-recursive wrapper

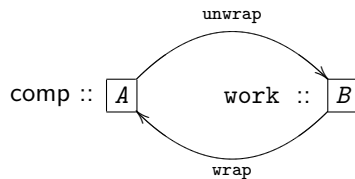
Questions about the Worker/Wrapper Transformation

- Is the technique actually correct?
- How can this be proved?
- Under what conditions does it hold?
- How should it be used in practice?

wrap and unwrap



wrap and unwrap in General



Prerequisites

$\text{comp} :: A$

$\text{comp} = \text{fix body}$ for some $\text{body} :: A \rightarrow A$

$\text{wrap} :: B \rightarrow A$ is a coercion from type B to A

$\text{unwrap} :: A \rightarrow B$ is a coercion from type A to B

$\text{wrap} \cdot \text{unwrap} = \text{id}_A$ *(basic worker/wrapper assumption)*

Derivation

$\text{comp} = \text{fix body}$

Prerequisites

$\text{comp} :: A$

$\text{comp} = \text{fix } \text{body} \text{ for some } \text{body} :: A \rightarrow A$

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Derivation

$\text{comp} = \text{fix } \text{body}$

$= \{ \text{id is the identity for } \cdot \}$

$\text{comp} = \text{fix } (\text{id} \cdot \text{body})$

Prerequisites

$\text{comp} :: A$

$\text{comp} = \text{fix body}$ for some $\text{body} :: A \rightarrow A$

$\text{wrap} :: B \rightarrow A$ is a coercion from type B to A

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Derivation

$\text{comp} = \text{fix body}$

$= \{ \text{id is the identity for } \cdot \}$

$\text{comp} = \text{fix} (\text{id} \cdot \text{body})$

$= \{ \text{assuming } \text{wrap} \cdot \text{unwrap} = \text{id} \}$

$\text{comp} = \text{fix} (\text{wrap} \cdot \text{unwrap} \cdot \text{body})$

Prerequisites

$\text{comp} :: A$

$\text{comp} = \text{fix body}$ for some $\text{body} :: A \rightarrow A$

$\text{wrap} :: B \rightarrow A$ is a coercion from type B to A

$\text{unwrap} :: A \rightarrow B$ is a coercion from type A to B

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Derivation

$\text{comp} = \text{fix body}$

$= \{ \text{id is the identity for } \cdot \}$

$\text{comp} = \text{fix} (\text{id} \cdot \text{body})$

$= \{ \text{assuming } \text{wrap} \cdot \text{unwrap} = \text{id} \}$

$\text{comp} = \text{fix} (\text{wrap} \cdot \text{unwrap} \cdot \text{body})$

$= \{ \text{rolling rule} \}$

$\text{comp} = \text{wrap} (\text{fix} (\text{unwrap} \cdot \text{body} \cdot \text{wrap}))$

Prerequisites

$\text{comp} :: A$

$\text{comp} = \text{fix body}$ for some $\text{body} :: A \rightarrow A$

$\text{wrap} :: B \rightarrow A$ is a coercion from type B to A

$\text{unwrap} :: A \rightarrow B$ is a coercion from type A to B

$\text{wrap} \cdot \text{unwrap} = \text{id}_A$ *(basic worker/wrapper assumption)*

Derivation

$\text{comp} = \text{fix body}$

$= \{ \text{id is the identity for } \cdot \}$

$\text{comp} = \text{fix} (\text{id} \cdot \text{body})$

$= \{ \text{assuming } \text{wrap} \cdot \text{unwrap} = \text{id} \}$

$\text{comp} = \text{fix} (\text{wrap} \cdot \text{unwrap} \cdot \text{body})$

$= \{ \text{rolling rule} \}$

$\text{comp} = \text{wrap} (\text{fix} (\text{unwrap} \cdot \text{body} \cdot \text{wrap}))$

$= \{ \text{define } \text{work} = \text{fix} (\text{unwrap} \cdot \text{body} \cdot \text{wrap}) \}$

$\text{comp} = \text{wrap work}$

$\text{work} = \text{fix} (\text{unwrap} \cdot \text{body} \cdot \text{wrap})$

Prerequisites

$\text{comp} :: A$

$\text{comp} = \text{fix body}$ for some $\text{body} :: A \rightarrow A$

$\text{wrap} :: B \rightarrow A$ is a coercion from type B to A

$\text{unwrap} :: A \rightarrow B$ is a coercion from type A to B

$\text{wrap} \cdot \text{unwrap} = \text{id}_A$ *(basic worker/wrapper assumption)*

Worker/Wrapper Theorem

If the above prerequisites hold, then

$\text{comp} = \text{fix body}$

can be rewritten as

$\text{comp} = \text{wrap work}$

where $\text{work} :: B$ is defined by

$\text{work} = \text{fix} (\text{unwrap} \cdot \text{body} \cdot \text{wrap})$

The Worker/Wrapper Assumptions

Key step of proof

```
fix (id · body)
= { assuming wrap · unwrap = id }
fix (wrap · unwrap · body)
```

We can actually use any of three different assumptions here

<code>wrap · unwrap</code>	<code>=</code>	<code>id</code>	(basic assumption)
		↓	
<code>wrap · unwrap · body</code>	<code>=</code>	<code>body</code>	(body assumption)
		↓	
<code>fix (wrap · unwrap · body)</code>	<code>=</code>	<code>fix body</code>	(fix-point assumption)

The Worker/Wrapper Recipe

Recipe

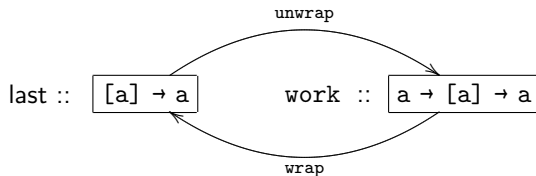
- Express the computation as a least fixed point;
- Choose the desired new type for the computation;
- Define conversions between the original and new types;
- Check they satisfy one of the worker/wrapper assumptions;
- Apply the worker/wrapper transformation;
- Simplify the resulting definitions.

We simplify to remove the overhead of the `wrap` and `unwrap` coercions, often using fusion, including the worker/wrapper fusion property.

The Worker/Wrapper Fusion Property

If $\text{wrap} \cdot \text{unwrap} = \text{id}$, then $(\text{unwrap} \cdot \text{wrap}) \text{ work} = \text{work}$

Creating Workers and Wrappers for last



```
wrap fn = \ xs -> case xs of
    [] -> error "last: []"
    (x:xs) -> fn x xs
```

```
unwrap fn = \ x xs -> fn (x:xs)
```

```
last = fix body
```

```
body last = \ v -> case v of
    []      -> error "last: []"
    (x:[]) -> x
    (x:xs) -> last xs
```

Testing the basic worker/wrapper assumption: Does $\text{wrap} \cdot \text{unwrap} = \text{id}$?

$\text{wrap} \cdot \text{unwrap}$

$= \{ \text{apply wrap, unwrap and } \cdot \}$

```
\ fn ->  
  (\ xs -> case xs of  
    [] -> error "last: []"  
    (x:xs) -> (\ x xs -> fn (x:xs)) x xs)
```

$= \{ \beta\text{-reduction} \}$

```
\ fn ->  
  (\ xs -> case xs of  
    [] -> error "last: []"  
    (x:xs) -> fn (x:xs))
```

Clearly not equal to $\text{id} :: ([a] \rightarrow a) \rightarrow ([a] \rightarrow a)$

Testing the body worker/wrapper assumption: Does `wrap · unwrap · body = body`?

```
wrap . unwrap . body
```

```
= { apply wrap, unwrap and · }
```

```
(\ fn ->  
  (\ xs -> case xs of  
    [] -> error "last: []"  
    (x:xs) -> (\ x xs -> fn (x:xs)) x xs))  
  (\ last v -> case v of  
    [] -> error "last: []"  
    (x:[]) -> x  
    (x:xs) -> last xs)
```

Testing the body worker/wrapper assumption: Does $\text{wrap} \cdot \text{unwrap} \cdot \text{body} = \text{body}$?

```
wrap . unwrap . body
```

```
= { apply wrap, unwrap and . }
```

```
= {  $\beta$ -reductions }
```

```
(\ fn ->
```

```
  (\ xs -> case xs of
```

```
    [] -> error "last: []"
```

```
    (x:xs) -> case (x:xs) of
```

```
      []      -> error "last: []"
```

```
      (x:[]) -> x
```

```
      (x:xs) -> fn xs))
```

Testing the body worker/wrapper assumption: Does $\text{wrap} \cdot \text{unwrap} \cdot \text{body} = \text{body}$?

```
wrap . unwrap . body
```

```
= { apply wrap, unwrap and . }
```

```
= {  $\beta$ -reductions }
```

```
= { case of known constructors }
```

```
(\ fn ->
```

```
  (\ xs -> case xs of
```

```
    [] -> error "last: []"
```

```
    (x:xs) -> case xs of
```

```
      [] -> x
```

```
      xs -> fn xs))
```

Testing the body worker/wrapper assumption: Does $\text{wrap} \cdot \text{unwrap} \cdot \text{body} = \text{body}$?

`wrap . unwrap . body`

= { apply wrap, unwrap and \cdot }
= { β -reductions }
= { case of known constructors }
= { common up case }

```
(\ fn ->  
  (\ xs -> case xs of  
    [] -> error "last: []"  
    (x:[]) -> x  
    (x:xs) -> fn xs))
```

Which equals `body`. QED.

Applying the Worker/Wrapper Transformation

Before

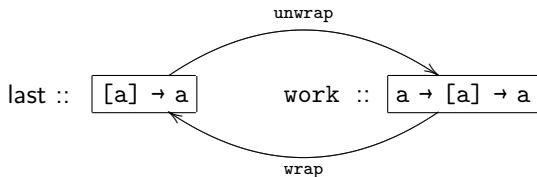
```
last = fix body
```

```
last :: [a] -> a
```

```
last = wrap work
```

```
work :: a -> [a] -> a
```

```
work = fix ( unwrap  
            . body  
            . wrap  
            )
```



Inline and Simplify

```
last  :: [a] -> a
last xs = case xs of
    [] -> error "last: []"
    (x:xs) -> work x xs

work  :: a -> [a] -> a
work = fix ( (\ fn x xs -> fn (x:xs))
    . (\ last v -> case v of
        []      -> error "last: []"
        (x:[]) -> x
        (x:xs) -> last xs)
    . (\ fn xs -> case xs of
        [] -> error "last: []"
        (x:xs) -> fn x xs)
    )
```

Inline and Simplify

```
last  :: [a] -> a
last xs = case xs of
    [] -> error "last: []"
    (x:xs) -> work x xs

work  :: a -> [a] -> a
work = fix ( \ fn x xs ->
    case (x:xs) of
        []      -> error "last: []"
        (x:[]) -> x
        (x:xs) -> case xs of
            [] -> error "last: []"
            (x:xs) -> fn x xs
    )
```

Inline and Simplify

```
last  :: [a] -> a
last xs = case xs of
    [] -> error "last: []"
    (x:xs) -> work x xs

work  :: a -> [a] -> a
work = fix ( \ fn x xs ->
    case xs of
        [] -> x
        xs -> case xs of
            [] -> error "last: []"
            (x:xs) -> fn x xs
    )
```

Inline and Simplify

```
last  :: [a] -> a
last xs = case xs of
    [] -> error "last: []"
    (x:xs) -> work x xs

work  :: a -> [a] -> a
work = fix ( \ fn x xs ->
    case xs of
        [] -> x
        (x:xs) -> fn x xs
    )
```

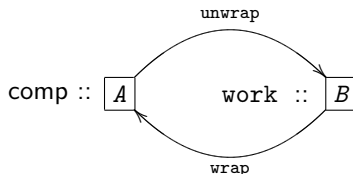
Inline and Simplify

```
last  :: [a] -> a
last xs = case xs of
    [] -> error "last: []"
    (x:xs) -> work x xs
```

```
work  :: a -> [a] -> a
work x xs = case xs of
    []      -> x
    (x:xs) -> work x xs
```

When does the Worker/Wrapper Transformation Succeed?

When $\text{unwrap} \cdot \text{wrap}$ fuse!



Emerging heuristic...

Simplification Friendly

Pre-conditions:

any of basic, body or fix
 $\text{unwrap} \cdot \text{wrap} = \text{id}_B$

When A is "larger" than B

Worker/Wrapper Fusion

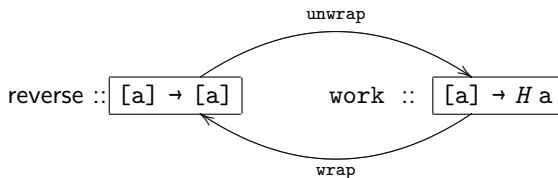
Pre-condition:

$\text{wrap} \cdot \text{unwrap} = \text{id}_A$

When B is "larger" than A

More powerful fusion methods can also be used

Creating Workers and Wrappers for reverse



```
type H a = [a] -> [a]
```

```
a2c :: H a -> [a]
```

```
a2c f = f []
```

```
c2a :: [a] -> H a
```

```
c2a xs = \ ys -> xs ++ ys
```

```
wrap fn = \ xs -> a2c (fn xs)
```

```
unwrap fn = \ xs -> c2a (fn xs)
```

Testing the basic worker/wrapper assumption: Does $\text{wrap} \cdot \text{unwrap} = \text{id}$?

$\text{wrap} \cdot \text{unwrap}$

$= \{ \text{apply wrap, unwrap} \}$

$(\lambda \text{ fn xs} \rightarrow \text{a2c (fn xs)}) \cdot (\lambda \text{ fn xs} \rightarrow \text{c2a (fn xs)})$

$= \{ \text{apply} \cdot \}$

$\lambda \text{ f} \rightarrow (\lambda \text{ fn xs} \rightarrow \text{a2c (fn xs)}) ((\lambda \text{ fn xs} \rightarrow \text{c2a (fn xs)}) \text{ f})$

$= \{ \beta\text{-reduction} \}$

$\lambda \text{ f} \rightarrow (\lambda \text{ fn xs} \rightarrow \text{a2c (fn xs)}) (\lambda \text{ xs} \rightarrow \text{c2a (f xs)})$

$= \{ \beta\text{-reduction} \}$

$\lambda \text{ f} \rightarrow (\lambda \text{ xs} \rightarrow \text{a2c ((\lambda \text{ xs} \rightarrow \text{c2a (f xs)}) \text{ xs}))$

$= \{ \beta\text{-reduction} \}$

$\lambda \text{ f} \rightarrow (\lambda \text{ xs} \rightarrow \text{a2c (c2a (f xs))})$

Does $a2c \cdot c2a = id$?

$a2c \cdot c2a$

$= \{ \text{apply } a2c, c2a \}$

$(\lambda f \rightarrow f []) \cdot (\lambda xs ys \rightarrow xs ++ ys)$

$= \{ \text{apply } \cdot \}$

$\lambda zs \rightarrow (\lambda f \rightarrow f []) ((\lambda xs ys \rightarrow xs ++ ys) zs)$

$= \{ \beta\text{-reduction} \}$

$\lambda zs \rightarrow (\lambda f \rightarrow f []) (\lambda ys \rightarrow zs ++ ys)$

$= \{ \beta\text{-reduction} \}$

$\lambda zs \rightarrow (\lambda ys \rightarrow zs ++ ys) []$

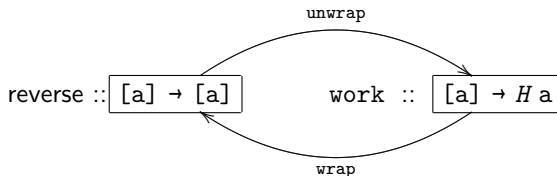
$= \{ \beta\text{-reduction} \}$

$\lambda zs \rightarrow zs ++ []$

$= \{ [] \text{ is the identity for } ++ \}$

$\lambda zs \rightarrow zs$

Improving Reverse



```
wrap fn = \ xs -> a2c (fn xs)
```

```
unwrap fn = \ xs -> c2a (fn xs)
```

```
body rev = \ v -> case v of
```

```
    []      -> []
```

```
    (x:xs) -> rev xs ++ [x]
```

```
reverse = wrap work
```

```
work = fix ( unwrap . body . wrap )
```

Improving Reverse (2)

```
reverse = (\ fn xs -> a2c (fn xs)) work

work = fix ( (\ fn xs -> c2a (fn xs))
            . (\ rev v -> case v of
                    []      -> []
                    (x:xs) -> rev xs ++ [x])
            . (\ fn xs -> a2c (fn xs))
            )
```

- Inline · and simplify using β -reduction.

Improving Reverse (3)

```
reverse xs = a2c (work xs)
```

```
work = fix (\ rev v -> c2a (case v of
                               []      -> []
                               (x:xs) -> a2c (rev xs) ++ [x])
           )
```

- We now have the structure to being something akin to rippling.
- Goal:
 - Move the `c2a` to just in front of `a2c`, giving `c2a (a2c rev xs)`
 - Unapply `unwrap` and `wrap`, giving `unwrap (wrap rev)`
 - Use the Worker/Wrapper fusion law

The Worker/Wrapper Fusion Property

If `wrap · unwrap = id`, then `(unwrap · wrap) work = work`

Improving Reverse (4)

```
reverse xs = a2c (work xs)
```

```
work = fix (\ rev v -> c2a (case v of
                             []      -> []
                             (x:xs) -> a2c (rev xs) ++ [x])
          )
```

- We use distribution over case to push `c2a` inside the case expression
- This relies on `c2a` being strict

Improving Reverse (4)

```
reverse xs = a2c (work xs)
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work = fix (\ rev v -> case v of
    []      -> c2a []
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- We use distribution over case to push `c2a` inside the case expression
- This relies on `c2a` being strict
- `c2a` has made progress towards our goal

Improving Reverse (4)

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reverse xs = a2c (work xs)
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work = fix (\ rev v -> case v of
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)
```

- We use distribution over case to push `c2a` inside the case expression
- This relies on `c2a` being strict
- `c2a` has made progress towards our goal
- `c2a [] = id` (by applying `c2a, ++`)

Improving Reverse (5)

```
reverse xs = a2c (work xs)
```

```
work = fix (\ rev v -> case v of
    []      -> id
    (x:xs) -> c2a (a2c (rev xs) ++ [x]))
)
```

- $c2a (e1 ++ e2) = c2a e1 \cdot c2a e2$

Improving Reverse (5)

```
reverse xs = a2c (work xs)
```

```
work = fix (\ rev v -> case v of
    []      -> id
    (x:xs) -> c2a (a2c (rev xs)) . c2a [x]
)
```

- $c2a (e1 ++ e2) = c2a e1 \cdot c2a e2$
- We can now unapply unwrap and wrap

Improving Reverse (5)

```
reverse xs = a2c (work xs)
```

```
work = fix (\ rev v -> case v of
    []      -> id
    (x:xs) -> (unwrap . wrap) rev xs . c2a [x]
)
```

- $c2a (e1 ++ e2) = c2a e1 \cdot c2a e2$
- We can now unapply `unwrap` and `wrap`
- And we can use the Worker/Wrapper Fusion Property

Improving Reverse (5)

```
reverse xs = a2c (work xs)
```

```
work = fix (\ rev v -> case v of
                []      -> id
                (x:xs) -> rev xs . c2a [x]
            )
```

- $c2a (e1 ++ e2) = c2a e1 \cdot c2a e2$
- We can now unapply unwrap and wrap
- And we can use the Worker/Wrapper Fusion Property
- We have removed the overhead of the coercion

Improving Reverse (5)

```
reverse xs = work xs []
```

```
work = fix (\ rev v -> case v of
                []      -> ys -> ys
                (x:xs) -> ys -> rev xs (x : ys)
            )
```

- After further uses of `apply`, we reach a clean implementation using `fix`
- We now can apply `fix` (and other small transformations)

Improving Reverse (5)

```
reverse xs = work xs []
```

```
work []      ys = ys
```

```
work (x:xs) ys = work xs (x:ys)
```

- After further uses of `apply`, we reach a clean implementation using `fix`
- We now can apply `fix` (and other small transformations)
- Efficient reverse!

Conclusions

- Worker/wrapper is a general and systematic approach to transforming a computation of one type into an equivalent computation of another type
- It is straightforward to understand and apply, requiring only basic equational reasoning techniques, and often avoiding the need for induction
- It allows many seemingly unrelated optimization techniques to be captured inside a single unified framework

Further Work

- Monadic and Effectful Constructions
- Mechanization
- Implement inside the Haskell Equational Reasoning Assistant
- Consider other patterns of recursion

www.workerwrapper.com