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Generic Incremental Computation for Regular Datatypes

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Title Explanation – Incremental Computation

Generic Incremental Computation for Regular Datatypes

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Incremental computation is an approach to improve performance by only recomputing result for changed input

Title Explanation – Example Incremental Computation

```haskell
fib :: Int -> Int
fib 0 = 0
fib 1 = 1
fib n = fib (n - 1) + fib (n - 2)
```

Call Hierarchy

```
                  fib(4)
              /          \
         fib(3)           fib(2)
          /   \            /   \
    fib(2)   fib(1) fib(1)   fib(0)
    /   \
fib(1)  fib(0)
```

Title Explanation – Example Incremental Computation

A technique for implementing incremental computations is:

Memoization

stores the result of a computation and returns the cached result when the same input occurs again.

Title Explanation – Example Incremental Computation

New Call Hierarchy

```
              fib(4)
          /             \
      fib(3)              fib(2)
       /    \
   fib(2)   fib(1)
    /    \
fib(1)  fib(0)
```

Function Call	Result
fib(2)	1
fib(3)	2
fib(4)	3

Cached Results

Title Explanation – Generic

Generic Incremental Computation for Regular Datatypes

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Generic refers to *datatype-generic programming*, which is a form of abstraction that allows defining functions that can operate on a large class of datatypes.

Title Explanation – Generic Example

```haskell
data List a = Nil | Cons a (List a) -- Haskell Notation [] | x : []

length :: List a -> Int
length Nil          = 0
length (Cons _ t) = 1 + length t

data Tree a = Leaf | Node (Tree a) a (Tree a)

length :: Tree a -> Int
length Leaf _         = 1
length (Node l _ r) = 1 + length l + length r
```

Title Explanation – Generic Example

```haskell
gLength :: (Generic f) => f a -> Int
gLength = ...
```

A *single* `length` function can be written, that can operate on lists, trees, and many other datatypes

```
> gLength (Cons 1 (Cons 2 (Cons 3 Nil))) -- List Int
  3

> gLength (Node Leaf 1 Leaf) -- Tree Int
  3
```

Title Explanation – Regular Datatypes

Generic Incremental Computation for Regular Datatypes

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Regular datatypes are recursive datatypes, which can only recurse into themselves, such as lists, binary trees, etc.

Title Explanation – Regular Datatypes Example

Regular Datatypes

```
data List a = Nil | Cons a (List a)

data Tree a = Leaf | Node a (Tree a) (Tree a)
```

Not Regular Datatypes

```
data Tree a = Empty | Node a (Forest a)

data Forest a = Nil | Cons (Tree a) (Forest a)
```

Title Explanation – Summary

Generic Incremental Computation for Regular Datatypes

- Improve performance by only recomputing changed input
- Using generic programming to define functionality for a large class of datatypes
- The class of datatypes are regular datatypes

Goal – What does this improve?

Goal

Implement an incremental algorithm which performs better than the non-incremental algorithm for large regular datatypes

Solution – Example with Memoization

```haskell
data Tree a = Leaf a | Node (Tree a) a (Tree a)

sumTree :: Tree Int -> Int
sumTree (Leaf x)     = x
sumTree (Node l x r) = x + sumTree l + sumTree r

exampleTree = Node (Node (Leaf 1) 3 (Leaf 2)) 5 (Node (Leaf 1) 3 (Leaf 2))
```

Visual representation

```
                 5
               /   \
sumTree(    3       3     ) = 17
           / \     / \
          1   2   1   2
```

Solution – Example with Memoization

Memoized version of the `sumTree`

Example Tree

```
     5
   /   \
  3     3
 / \   / \
1   2 1   2
```

Tree	Result
`5`	
`/ \`	
`3 3`	17
`/ \ / \`	
`1 2 1 2`	
`3`	
`/ \`	6
`1 2`	

Cached Results

Solution – Using Hash function

A *hash function* is a process of transforming input into an arbitrary fixed-size value (i.e., digest), where the same input always generates the same output

```
     5
   /   \
  3     3           ->    1da16c7c48e429b4ad6e6c88d941d2bd
 / \   / \
1   2  1   2                          Digest
```

The comparison for equality is now **constant** time instead of *linear*.

Solution – Storing the Digests

A *Merkle Tree* is a data structure which integrates the *digests*, which represents the internal structure, within the data structure

```
data TreeH a = LeafH Digest a
             | NodeH Digest (TreeH a) a (TreeH a)
```

```
merkle :: Tree Int -> TreeH Int
merkle l@(Leaf x)     = LeafH (hash l) x
merkle b@(Node l x r) = NodeH (hash b) l' x r'
  where
    l' = merkle l
    r' = merkle r
```

Solution – Efficiently updating the Input

The *Zipper* is a technique for keeping track of how the data structure is being traversed through

```
     5                            5
   /   \                           \
  3     3      ->      3            3
 / \   / \            / \          / \
1  2   1  2          1   2        1   2
```

Go to the left Subtree of the Tree

Solution – Efficiently updating the Input

```
          5                     5                 5
           \                     \              /   \
  3         3     ->     7        3     ->     7     3
 / \       / \            / \      / \            / \   / \
1   2     1   2        4   3    1   2        4  3   1  2
```

When updating the data structure of the input. Only the parent node digests needs to be updated. Which is more efficient than rehashing the entire tree.

Generic Programming – Pattern Functors

Primitive Type Constructors

```
data U r         = U                -- Empty constructor
data I r         = I r              -- Recursive position
data K a r       = K a              -- Constant
data (f :+: g) r = L (f r) | R (g r) -- Sums (Choice)
data (f :*: g) r = (f r) :*: (g r)   -- Products (Combine)
```

Pattern functor for the `Tree` datatype

```
data Tree a = Leaf a | Node (Tree a) a (Tree a)

type instance PF (Tree a) = K a                    -- Leaf
                          :+: (I :*: K a :*: I) -- Node
```

Generic Implementation – Hashing Primitive Type Constructors

```
class Hashable f where
  hash :: f (Merkle g) -> Digest
```

- The `f` represents the primitive type constructors (i.e., `U`, `I`, `K`, `:+:`, `:*:`)
- The `Merkle g` is the type of the recursive position (i.e., `I r`).
- `Merkle g` contains the `Digest` of its internal structure.
- The `hash` function only converts a single layer of the pattern functor.

Generic Implementation – Hashing Primitive Type Constructors

```
instance Hashable U where
  hash _ = hash "U"

instance (Show a) => Hashable (K a) where
  hash (K x) = digestConcat [hash "K", hash x]
```

Generic Implementation – Hashing Primitive Type Constructors

```haskell
instance (Hashable f, Hashable g) => Hashable (f :+: g) where
  hash (L x) = digestConcat [hash "L", hash x]
  hash (R x) = digestConcat [hash "R", hash x]

instance (Hashable f, Hashable g) => Hashable (f :*: g) where
  hash (x :*: y) = digestConcat [hash "P", hash x, hash y]
```

Generic Implementation – Hashing Primitive Type Constructors

```
class Hashable f where
  hash :: f (Merkle g) -> Digest

instance Hashable I where
  hash (I x) = digestConcat [digest "I", getDigest x]
    where
      getDigest :: Fix (f :*: K Digest) -> Digest
      getDigest (In (_ :*: K h)) = h
```

Generic Implementation – Generic Merkle Tree

```
merkleG :: Hashable f => f (Merkle g) -> (f :*: K Digest) (Merkle g)
merkleG f = f :*: K (hash f)

merkle :: (Regular a, Hashable (PF a), Functor (PF a))
       => a -> Merkle (PF a)
merkle = In . merkleG . fmap merkle . from
```

Generic Implementation – Cata Merkle

cata means *catamorphism* which is a generalization of a *fold*. A fold combines the data structure into a single value (e.g., sumTree is a fold).

```
cataMerkleState :: (Functor f, Traversable f)
                => (f a -> a) -> Merkle f -> State (HashMap Digest a) a
cataMerkleState alg (In (x :*: K d))
  = do m <- get
       case lookup d m of
         Just a  -> return a
         Nothing -> do y <- mapM (cataMerkleState alg) x
                       let r = alg y
                       modify (insert d r) >> return r
```

Generic Implementation – Cata Sum

```
cataSum :: Merkle (PF (Tree Int)) -> (Int, HashMap Digest Int)
cataSum = cataMerkle
  (\case
    L (K x)                   -> x
    R (I l :*: K x :*: I r) -> l + x + r
  )

> cataSum (merkle (Node (Leaf 1) 2 (Leaf 3)))
    (6, {"931090e5": 1, "7d1ef1c9": 3, "ba811ed5": 6})
```

Generic Implementation – Pattern Synonyms

Pattern synonyms add an abstraction over patterns, which allows the user to move additional logic from guards and case expressions into patterns.

```
cataSum :: Merkle (PF (Tree Int)) -> (Int, HashMap Digest Int)
cataSum = cataMerkle
  (\case
    Leaf_ x     -> x
    Node_ l x r -> l + x + r
  )
```

Experiments – Method

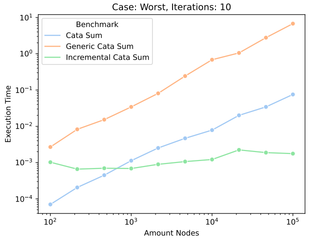
Three functions:

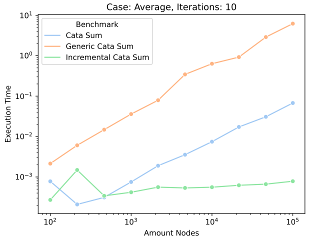
- `Cata Sum`
  - Non-incremental algorithm
- `Generic Cata Sum`
  - Incremental algorithm with an empty cache
- `Incremental Cata Sum`
  - Incremental algorithm with a filled cache

Three scenarios:

• Worst case:	updates the lowest left leaf with a new leaf
• Average case:	updates a node in the middle of the data structure with a new leaf
• Best case:	updates the left child of the root-node with a new leaf

Experiments – Results - Execution Time





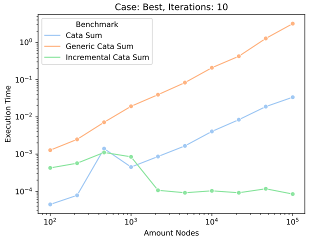


Figure: The execution time over 10 executions for the Worst, Average and Best case.

Experiments – Results - Memory Usage

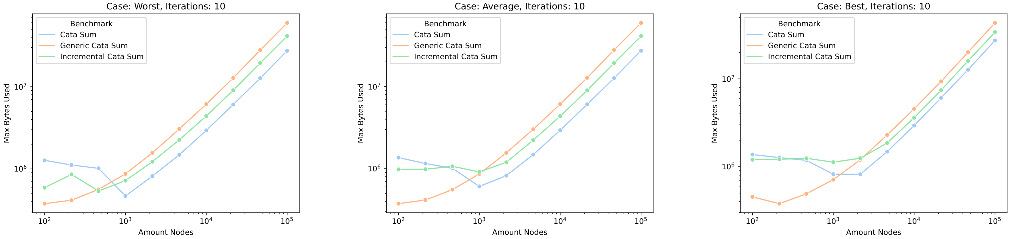


Figure: The max-bytes-used over 10 executions for the Worst, Average and Best case.

Conclusion – Undiscussed Topics

- The explanation of fixed-point
- Implementation of the generic Zipper
- Cache management
- Future work
- Explained what generic library is chosen and why it was chosen

Conclusion – Summary

- We have implemented an efficient incremental algorithm over regular datatypes
- The incremental algorithm is faster than the non-incremental version when the data structure contains more than 10^3 nodes
- We introduced the pattern synonyms to improve the developer experience to almost the same level as the non-incremental implementation
- However, the initial pass of the incremental algorithm is a lot slower than the non-incremental version. Therefore, the incremental algorithm needs to be performed a lot (with small changes), before being overall faster than the non-incremental version.