The functional essence of imperative binary search trees

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Functional programming 101 : list reversal

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

reverse :: List a -> List a
reverse xs = reverseAcc xs Nil

  where
  reverseAcc :: List a -> List a -> List a
  reverseAcc Nil acc = acc
  reverseAcc (Cons x xs) acc = reverseAcc xs (Cons x acc)
```

```haskell
```
Pure functional programming

*Compositional* programs - each assembled from other functions that can be tested and verified independently.

There are a variety of *elementary* techniques for verifying that a program is correct:

- testing automatically;
- writing pen and paper proofs;
- developing a formal proofs using proof assistants.
Pure functional programming

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- testing automatically;
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- developing a formal proofs using proof assistants.

How does this compare to list reversal in an imperative language?
list_t* reverse( list_t* curr ) {
    list_t* prev = NULL;
    while (curr != NULL) {
        list_t* next = curr->tail;
        curr->tail = prev;
        prev = curr;
        curr = next;
    }
    return prev;
}

Each cell in the list stores a value and a pointer to the remaining lists.

To reverse the list, we update the pointer in each cell to point to the previous element, until there are no cells left.
In-place execution

prev
Nil

cur

Cons 1 → Cons 2 → Cons 3 → Nil
In-place execution
In-place execution
In-place execution
Correctness?

Giving a *formal proof* that such a program is correct is **very hard**.

- Hoare logic is not suitable for reasoning about this kind of imperative code: what if the list structure in memory has cycles? Or if the two pointers map to lists sharing the same memory locations?
- Extensions of Hoare logic, notably separation logic, have had a lot of success - but these methods are certainly not elementary.
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- Hoare logic is not suitable for reasoning about this kind of imperative code: what if the list structure in memory has cycles? Or if the two pointers map to lists sharing the same memory locations?
- Extensions of Hoare logic, notably separation logic, have had a lot of success - but these methods are certainly not elementary.

But the C algorithm has an important property: it is executed *in-place* - it does not need to allocate new memory or deallocate unused memory.
Functional reverse

reverseAcc :: List a → List a → List a

reverseAcc Nil acc = acc

reverseAcc (Cons x xs) acc = reverseAcc xs (Cons x acc)
Towards in-place functional programming

reverseAcc :: List a → List a → List a

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In-place functional programming

\[
\text{reverseAcc} :: \text{List } a \rightarrow \text{List } a \rightarrow \text{List } a
\]

\[
\text{reverseAcc } \text{Nil } \text{acc } = \text{acc}
\]

\[
\text{reverseAcc } (\text{Cons } x \text{ xs}) \text{acc } = \text{reverseAcc } \text{xs } (\text{Cons } x \text{ acc})
\]

The reverseAcc function has a few important properties:

• we can see that we are matching on one Cons cell on the left;

• and allocating one new Cons cell on the right.

• all other variables (like \(x\) or \(\text{acc}\)) are used linearly, i.e. they are not copied or discarded.

We will call such programs \textit{fully in-place} – or fip for short.
Making this more precise..

Fig. 4. Well-formed FIP expressions, where the multiplicity of each variable in $\Gamma$ is 1.
In-place reverse in Koka

These rules (and corresponding memory reuse) have been implemented in the Koka compiler.

Re-implementing the reverse function in Koka becomes:

```
fip fun reverse-acc( xs : list<a>, acc : list<a> ) : list<a>
    match xs
        Cons(x,xx) ↦ reverse-acc( xx, Cons(x,acc) )
        Nil ↦ acc
```

The `fip` keyword indicates that a function can be executed fully in place.

The compiler checks that each function with the `fip` annotation can be executed without (de)allocating memory.
List reversal is not so interesting - what about algorithms for trees?

```typescript
type tree
  Node( left : tree, key : int, right : tree )
  Leaf
```

Let's look at algorithms on binary search trees.

In particular, restructuring binary search trees, where accessing an element restructures the tree.
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Let's look at algorithms on binary search trees.

In particular, restructuring binary search trees, where accessing an element restructures the tree.

We aim to define an access function:

```haskell
fun access-spec (t : tree, k : key) : tree
    Node (smaller(t,k), k, bigger(t,k))
```

which inserts the key, if it is not yet present, and moves it to the root if it is.
**Rotation (Allen & Munro, 1976)**

\[ \text{fun rotateRight (t : tree): tree} \]

\[ \text{match t} \]

\[ (\text{Node (Node (t2, a, t3), f, t1) \rightarrow Node (t2, a, Node (t3, f, t1))} \]
Allen & Munroe suggest *repeated* rotations, ensuring the key being looked up is moved to the root of the new binary tree.

In this fashion, frequently accessed elements naturally ‘bubble up’ to the root of the tree.

Can we give a purely functional—yet in place—algorithm?
fun lookup (k : int, t : tree)

match t with
    Node (l, x, r) -> if k == x
        then x
        else if k < x
            then lookup (k, l)
            else lookup (k, r)

This is not in place: we only ever recurse on one subtree.
Warm up; look up

```ocaml
fun lookup (k : int, t : tree)
  match t with
  Node (l, x, r) -> if k == x
    then x
    else if k < x
      then lookup (k, l)
      else lookup (k, r)
```

This is not in place: we only ever recurse on one subtree.

**Key idea**

Search through the tree recursively, accumulating the unvisited subtrees on a ‘stack’.

Once we find the element, unwind the ‘stack’ to rebuild the new tree, rotating as we move back up.
A simple stack of subtrees will not work – to reconstruct a binary search tree we need to record if we went left or right!

```go
type zipper

Done

// we went left; the tree stores bigger elements than the key being accessed
Left(up : zipper, x : int, right : tree )

// we went right; the tree stores smaller elements than the key being accessed
Right(left : tree, x : int, up : zipper )
```
A simple stack of subtrees will not work – to reconstruct a binary search tree we need to record if we went left or right!

```go
type zipper
  Done
  // we went left; the tree stores bigger elements than the key being accessed
  Left(up : zipper, x : int, right : tree )
  // we went right; the tree stores smaller elements than the key being accessed
  Right(left : tree, x : int, up : zipper )
```

Using these zippers we can construct a pair of functions:

```go
// search through the tree for the given key
fun access (key : int, t : tree, z : zipper) : (tree, zipper)
// rebuild the entire tree, rotating as necessary
fun rebuild (t : tree, z : zipper) : tree
```
Accessing a given key

\[ fip(1) \textbf{fun} \ \text{access}(t : \text{tree}, \ k : \text{int}, \ z : \text{zipper}) \]

\[
\text{match } t \\
\quad \text{Node}(l, x, r) : \rightarrow \textbf{if} \ x == k \ \textbf{then} \ \text{rebuild}(z, \ \text{Node}(l,k,r)) \\
\quad \quad \quad \textbf{else if} \ k < x \ \textbf{then} \ \text{access}(l, k, \ \text{Left}(z,x,r)) \\
\quad \quad \quad \textbf{else} \ \text{access}(r, k, \ \text{Right}(l,x,z)) \\
\quad \text{Leaf} \quad \rightarrow \ \text{rebuild}(z, \ \text{Node}(\text{Leaf},k,\text{Leaf}) \ )
\]

The access function has the same structure as the (more familiar) lookup function.

If the key is already present, the tree is restructured; otherwise the new key is inserted.

The function is in-place, but may do at most one allocation.
In-place reuse

\[
\text{fip fun access (} \ldots \text{)} \\
\quad \text{Node}(l,x,r) \rightarrow \text{if } \ldots \text{ then access}(l, k, \text{Left}(z,x,r))
\]

Why is this in-place? We match on a node, but extend our zipper?
fip fun access (...)

Node(l,x,r) \rightarrow if ... then access(l, k, Left(z,x,r))

Why is this in-place? We match on a node, but extend our zipper?

Memory re-use is *not* restricted to the same constructors or even the same types!

Instead, we only check that the variables are not duplicated or discarded;

And that the *sizes* of deallocations and allocations line up.
Reconstructing the tree

```haskell
fip fun rebuild(z : zipper, t : tree )
  match z
    Done       -> t
    Right(l,x,z) -> match t // we went right looking for k
                          Node(s,k,b) -> rebuild(z, Node(Node(l,x,s), k, b))
    Left(z,x,r) -> match t // we went left looking for k
                          Node(s,k,b) -> rebuild(z, Node(s, k, Node(b,x,r)))
```

Now we rebuild the entire tree, popping elements off the zipper.

In each case, we rotate the tree as required to ensure the result remains a binary search tree.

From this definition, it is easy to see that the key \( k \) stays at the root – just as we wanted!
How do you come up with code like this?

fun access(t: tree, k: key)
match t
       Node(l,x,r) -> if x < k then match access(r,k) // lookup and rotate
                              Node(Node(l,x,s), y, b) -> Node(Node(l,x,s), y, b)
       else Leaf -> Node(Leaf, k, Leaf)
               elif x > k then match access(l,k) // lookup and rotate
                              Node(s,y,b) -> Node(s,y,Node(b,x,r))
               else Node(l,k,r)
Zippers - defunctionalised continuations

How do you come up with code like this?

It is ‘just’ the tail recursive version arising from the defunctionalised CPS-transformed direct implementation that is in-place, but not tail recursive:

```hs
fun access( t : tree, k : key )
    match t
        Node(l,x,r) → if x < k then match access(r,k) // lookup and rotate
            Node(s,y,b) → Node( Node(l,x,s), y, b)
        elif x > k then match access(l,k) // lookup and rotate
            Node(s,y,b) → Node( s, y, Node(b,x,r))
        else Node(l,k,r)
            Leaf → Node(Leaf,k,Leaf)

And the implementation above follows calculationally from the original access-spec.
Towards *constructor contexts*

The zippers are used as a ‘stack of trees’ – we have immediate access to the tree we last added to the zipper.

But that’s not always what we want: many *top down* algorithms work by *accumulating* (unfinished) trees, extending the tree with new nodes at the fringe.
Towards constructor contexts

The zippers are used as a ‘stack of trees’ – we have immediate access to the tree we last added to the zipper.

But that’s not always what we want: many top down algorithms work by accumulating (unfinished) trees, extending the tree with new nodes at the fringe.

Consider the following fragment of code from the previous slide:

```
Node(l,x,r) ->
  if x < k then match access(r,k) // lookup and rotate
    Node(s,y,b) -> Node(Node(l,x,s), y, b)
...
```

We could implement these unfinished trees as zippers, just as we could implement queues using lists...
Koka’s constructor contexts

Koka lets you write constructor contexts, or elements of an algebraic datatypes with a single hole:

```
Node(Leaf, 3, □)
```
Koka’s constructor contexts

Koka let’s you write *constructor contexts*, or elements of an algebraic datatypes with a single hole:

```
Node(Leaf, 3 , □)
```

There are two operations on these contexts:

```
fun (++) : ctx -> ctx -> ctx  // append contexts
fun (++.): ctx -> tree -> tree // fill in the hole
```
Tail recursive map

Using such contexts, we can write a tail recursive map function in a single pass:

```fsharp
fip fun map-td(xs : list<a>, f : a → b, acc : list-ctx<b> ) : list<b>
    match xs
        Cons(x,xs) → map-td( xx, f, acc ++ Cons(f(x), □) )
    Nil → acc ++ Nil
```

And start our map with an empty accumulator:

```fsharp
fip fun map(xs,f)
    map-td(xs, f, □)
```

This pattern – accumulating (partial) results in a constructor context – pops up again and again.
Implementing constructor contexts

We could implement constructor contexts using functions – similar to ‘difference lists’ – or zippers.
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We could implement constructor contexts using functions – similar to ‘difference lists’ – or zippers. But instead, we represent them as ‘Minamide tuples’, allocating an additional pointer to the context’s hole.

Then *all* operations on constructor contexts require constant time.
Towards top down move to root trees

Let's take a closer look at the direct implementation:

\[
\text{Node}(l, x, r) \rightarrow \\
\quad \text{if } x < k \text{ then match access}(r, k) \quad \text{// lookup and rotate} \\
\quad \text{Node}(s, y, b) \rightarrow \text{Node} (\text{Node}(l, x, s), y, b) \\
\]

\[\ldots\]

We can also phrase this in terms of two accumulating constructor contexts – the left and right subtrees – where we collect the parts of the trees we do not visit.
Top down move to root trees

\( \text{fip}(1) \) fun access-td(t : tree, k : key, accl : ctx, accr : ctx) : tree

match t

Node(l, x, r) →

if x < k then access-td(r, k, accl ++ Node(l, x, □), accr )
elif x > k then access-td(l, k, accl, accr ++ Node(□, x, r) )
else Node( accl ++. l, x, accr ++. r )

Leaf → Node( accl ++. Leaf, k, accr ++. Leaf)
Fast and correct

• The resulting Koka functions are *fast*, with performance on par with C!
• The functional algorithms are easy to verify, relating them to the (slow) functional spec.
• The functional algorithms capture the *essence* of the imperative pointer algorithms.
What about the imperative implementations?
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Fig. 1. The move-to-root top-down algorithm formalized in AddressC on the left, versus a screenshot of Stephenson’s published algorithm on the right.
Verifying imperative version

Using a proof assistant, we have given a formal proof of correctness of both top-down and bottom-up move to root trees.

That is, we can prove a Hoare triple of (roughly) the following form:

```plaintext
Lemma heap_mtr_insert_td_correct (k : key) (p : ptr) (t : tree) :
    { is_tree t p }
    heap_mtr_insert_td k p
    { is_tree (mtr_insert_td k t) p }.
```

In this way, we prove that the functional version (mtr_insert_td) coincides precisely with the (published) imperative algorithms (heap_mtr_insert_td).
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That is, we can prove a Hoare triple of (roughly) the following form:

\[
\text{Lemma } \text{heap\_mtr\_insert\_td\_correct} \ (k : \text{key}) \ (p : \text{ptr}) \ (t : \text{tree}) : \\
\{ \text{is\_tree} \ t \ p \} \\
\text{heap\_mtr\_insert\_td} \ k \ p \\
\{ \text{is\_tree} \ (\text{mtr\_insert\_td} \ k \ t) \ p \}.
\]

In this way, we prove that the functional version (mtr\_insert\_td) coincides precisely with the (published) imperative algorithms (heap\_mtr\_insert\_td).

Formal verification exposes the \textit{granite} of functional programming, rather than the mere \textit{limestone} of imperative algorithms.
Verifying the imperative version

- These proofs are non-trivial! If you've ever tried to write out a formal proof in Hoare logic for any program longer than 5 lines, you know there is a lot of bookkeeping involved.
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• The functional implementation captures the key parts of the specification – it is essential for spelling out the loop invariant.

• This is (to the best of our knowledge) the first formal proof of these algorithms.
Move-to-root trees guarantee that a freshly accessed key always moves to the root.

But it does not do any *rebalancing* along the way...
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But it does not do any *rebalancing* along the way...

The more established *splay trees* (Sleator and Tarjan 1985) address precisely this issue.

The key difference is in the *rebuild* function that tries to rebalance the resulting tree.

Similarly, the more recent *zip trees* (Tarjan et al. 2021) can be shown to have a fully in-place functional counterpart.
Comparing the same algorithm across different languages is always going to be unfair.

- Koka, Haskell, and OCaml have automatic memory management - as opposed to C;
- Haskell and OCaml use mark-and-sweep garbage collectors; Koka uses reference counting.
- Koka uses arbitrary precision integers for keys and all comparisons and arithmetic operations include branches for the case where big integer arithmetic is required;
- Haskell is lazy, most other functional languages are not.
10M pseudorandom insertions of a key between 0 and 100,000 on an initially empty tree.
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We start with a simple functional specification, access-spec.

We write a ‘direct style’ recursive implementation.

Transforming this to fip functions is guaranteed to produce fast code.
Conclusions

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• Elementary verification techniques only! Structural induction on trees suffices.

• Modern proof assistants can relate the functional and imperative versions - the functional algorithm captures the essence of the loop invariant.

• But if you need to write the functional version to verify imperative code – why write imperative programs to begin with?
Questions?
When to execute in place?

Even if a function is fip, it is not *always* safe to execute it in place.

Consider the following example:

```plaintext
fun makePalindrome(xs : list<a>) : list<a>
    return (append(xs, reverse(xs))
```

Clearly this call to reverse should not run in place!
Even if a function is fip, it is not *always* safe to execute it in place.

Consider the following example:

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fun makePalindrome( xs : list<a>) : list<a>
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Clearly this call to `reverse` should not run in place!

When can we tell it is safe to execute fip functions in place?
Koka uses a reference counted garbage collection.

As a result, we know at execution time how many references exist to any given value.

We can check if a reference is unique at run-time and re-use existing memory locations when possible:

```fip
fun reverse-acc( xs : list<a>, acc : list<a> ) : list<a>

match xs
  Cons(x,xx) ->
    val addr = if is-unique(xs) then &xs else { dup(x); dup(xx); decref(xs); alloc(2) }
    reverse-acc( xx, Cons@addr(x,acc) )...
```
The original zipper paper describes a functional approach to navigating through a tree (Huet 1997).

A pair of a zipper and tree, allows you to ‘move focus’ to a child, without loss of information:

```haskell
fip fun left (t : tree, z : zipper) : (tree, zipper)
  match t
    Node (l, x, r) → (l, Left(z,x,r))
```

Huet (1997) writes: Efficient destructive algorithms on binary trees may be programmed with these completely applicative primitives, which all use constant time, since they all reduce to local pointer manipulation.

Using our fip calculus we can make this precise – and check this property statically!

Zipper-based traversal turn out to be very useful.
### Zippers

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Zipper-based traversal turn out to be very useful.
Schorr-Waite-Deutsch style map on trees

**fip fun** load (t : tree, f : int -> int, z : zipper) : tree

  match t
  Node (l, x, r) -> load(l,f,Left(z, f(x), r))
  Leaf          -> unload(z,f,Leaf)

**fip fun** unload (z : zipper, f : int -> int, t : tree) : tree

  match z
  Left (z,x,r)   -> load(r,f,Right(t,x,z))
  Right (l,x,z)  -> unload(z,f,Node(l,x,t))
  Done           -> t

This traversal does not allocate any heap or stack space – yet works for any* data type!
Rebuilding splay trees

Self-Adjusting Binary Search Trees

DANIEL DOMINIC SLEATOR AND ROBERT ENRIQUE TARJAN

AT&T Bell Laboratories, Murray Hill, NJ

(a)

(b)

(c)
fun rebuild(z : zipper, t : tree) : tree

match tree

Node(tl,tx,tr) -> match z

Done -> Node(tl,tx,tr)

Right(rl,rx,Done) -> Node(Node(rl,rx,tl),tx,tr) // zig

Left(Done,lx,lr) -> Node(tl,tx,Node(tr,lx,lr))

Right(r1,rx,Right(l,x,up)) -> rebuild(up, Node(Node(l,x,r1),rx,tl),tx,tr)) // zigzig

Left(Right(l,x,up),lx,lr) -> rebuild(up, Node(Node(l,x,tl),tx,Node(tr,lx,lr)))

Right(r1,rx,Left(up,x,r)) -> rebuild(up, Node(Node(r1,rx,tl),tx,Node(tr,x,r))) // zigzag

Left(Left(up,x,r),lx,lr) -> rebuild(up, Node(tl,tx,Node(tr,lx,Node(lr,x,r)))))
So what’s our the papers

• In place versions of:
  • Splay trees;
  • Schorr Waite traversal of trees;
  • Generic map over any algebraic datatype;
  • Red black tree insertion;
  • Mergesort;
  • Finger tree insertions;
  • ...

• Top-down & bottom-up implementations of:
  • move to root trees;
  • splay trees;
  • zip trees;
  • proofs that they ‘are all equal’;
  • proofs that the functional versions coincide with published imperative ones.

• Lots of metatheory, showing that it is safe to execute fip programs in place.