


Proving tree algorithms for succinct data structures

Reynald Affeldt 


National Institute of Advanced Industrial Science and Technology, Japan
reynald.affeldt@aist.go.jp

Jacques Garrigue 

Graduate School of Mathematics, Nagoya University, Japan
garrigue@math.nagoya-u.ac.jp

Xuanrui (Ray) Qi¹ 

Department of Computer Science, Tufts University, United States
xqi01@cs.tufts.edu

Kazunari Tanaka 

Graduate School of Mathematics, Nagoya University, Japan
tanaka.kazunari@k.mbox.nagoya-u.ac.jp

Abstract

Succinct data structures give space-efficient representations of large amounts of data without sacrificing performance. They rely on cleverly designed data representations and algorithms. We present here the formalization in Coq/SSReflect of two different tree-based succinct representations and their accompanying algorithms. One is the Level-Order Unary Degree Sequence, which encodes the structure of a tree in breadth-first order as a sequence of bits, where access operations can be defined in terms of Rank and Select, which work in constant time for static bit sequences. The other represents dynamic bit sequences as binary balanced trees, where Rank and Select present a low logarithmic overhead compared to their static versions, and with efficient insertion and deletion. The two can be stacked to provide a dynamic representation of dictionaries for instance. While both representations are well-known, we believe this to be their first formalization and a needed step towards provably-safe implementations of big data.

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1 Introduction

Succinct data structures [13] represent combinatorial objects (such as bit vectors or trees) in a way that is space-efficient (using a number of bits close to the information theoretic lower bound) and time-efficient (i.e., not slower than classical algorithms). This topic is attracting all the more attention as we are now collecting and processing large amounts of data in various domains such as genomes or text mining. As a matter of fact, succinct data structures are now used in software products of data-centric companies such as Google [10].

¹ This work was performed while the author was visiting the Graduate School of Mathematics, Nagoya University.



The more complicated a data structure is, the harder it is to process it. A moment of thought is enough to understand that constant-time access to bit representations of trees requires ingenuity. Succinct data structures therefore make for intricate algorithms and their importance in practice make them perfect targets for formal verification [20].

In this paper, we tackle the formal verification of tree algorithms for succinct data structures. We first start by formalizing basic operations such as counting (**rank**) and searching (**select**) bits in arrays. This is an important step because the theory of these basic operations sustains most succinct data structures. Next, we formally define and verify a bit representation of trees called Level-Order Unary Degree Sequence (hereafter LOUDS). It is for example used in the Mozc Japanese input method [10]. The challenge there is that this representation is based on a level-order (i.e., breadth-first) traversal of the tree, which is difficult to describe in a structural way. Nonetheless, like most succinct data structures, this bit representation only deals with static data. Last, we further explore the advanced topic of dynamic bit vectors. The implementation of the latter requires to combine static bit vectors from succinct data structures with classical balanced trees. We show in particular how this can be formalized using a flavor of red-black trees where the data is in the leaves (rather than in the internal nodes, as in most functional implementations).

In both cases, our code can be seen as a verified functional specification of the algorithms involved. We were careful to use the right abstractions in definitions so that this specification could be easily translated to efficient code using arrays. For LOUDS we only rely on the **rank** and **select** functions; we have already provided an efficient implementation for **rank** [20]. For dynamic bit vectors, while the code we present here is functional, it closely matches the algorithms given in [13]. We did prove all the essential correctness properties, by showing the equivalence of each operation with its functional counterpart (functions on inductive trees for LOUDS, and on sequences of bits for dynamic bit vectors).

Independently of this verified functional specification, we identify two technical contributions, that arised while doing this formalization. One is the notion of level-order traversal up to a path in a tree, which solves the challenge of performing path-induction on a level-order traversal. Another is our experience report with using small-scale reflection to prove algorithms on inductive data, which we hope could provide insights to other researchers.

The rest of this paper is organised as follows. The next section introduces **rank** and **select**. Section 3 describes our formalization of LOUDS, including the notion of level-order traversal up to a path. Section 4 uses trees to represent bit vectors, defining not only **rank** and **select**, but also insertion and deletion. Section 5 reports on our experience. Section 6 compares with the litterature, and Section 7 concludes.

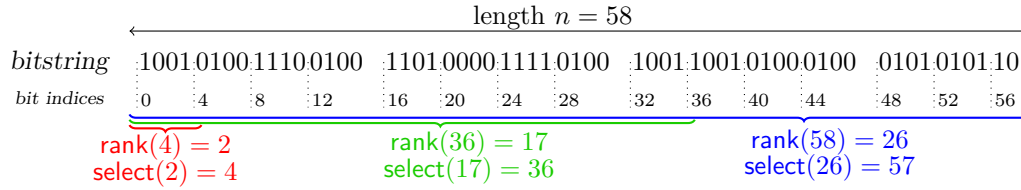
2 Two functions to build them all

The **rank** and **select** functions are the most basic blocks to form operations on succinct data structures: **rank** counts bits while **select** searches for their position. The rest of this paper (in particular Sect. 3.2 and Sect. 4) explains how they are used in practice to perform operations on trees. In this section, we just briefly explain their formalization and theory.

2.1 Counting bits with rank

The **rank** function counts the number of elements **b** (most often bits) in the prefix (i.e., up to some index **i**) of an array **s**. It can be conveniently formalized using standard list functions:

Definition `rank b i s := count_mem b (take i s).`



■ **Figure 1** Examples of rank and select queries on a sample bitstring (bit indexed from 0 to 57)

Figure 1 provides several examples of `rank` queries. The mathematically-inclined reader can alternatively² think of `rank` as the cardinal of the number of indices of `b` bits in a tuple `B`:

Definition `Rank (i : nat) (B : n.-tuple T) :=`
`#| [set k : [1,n] | (k <= i) && (tacc B k == b)] |.`

In this definition, `[1,n]` is the type of integers between 1 and n ; `tacc` accesses the tuple counting the indices from 1.

2.2 Finding bits with select

Intuitively, compared with `rank`, `select` performs the converse operation: it returns the *minimum* index of a bit in an array. It is conveniently specified using the `ex_minn` construct of the SSREFLECT library [6]:

Variables `(T : eqType) (b : T) (n : nat).`
Lemma `select_spec (i : nat) (B : n.-tuple T) :`
`exists k, ((k <= n) && (Rank b k B == i)) || (k == n.+1) && (count_mem b B < i).`
Definition `Select i (B : n.-tuple T) := ex_minn (select_spec i B).`

With this definition, `select` returns the index of the sought bit *plus one* (counting indices from 0); selecting the 0th bit always returns 0; when no adequate bit is found, `select` returns the size of the array plus one. The need for the 0 case explains why it makes sense to return indices starting from 1. Figure 1 provides several examples to illustrate the `select` function.

2.3 The theory of rank and select

The `rank` and `select` functions are used in a variety of applications whose formal verification naturally calls for a shared library of lemmas. Our first work is to identify and isolate this theory. Its lemmas are not all difficult to prove. For instance, the fact that `Rank` cancels `Select` directly follows from the definitions:

Lemma `SelectK n (s : n.-tuple T) (j : nat) :`
`j <= count_mem b s -> Rank b (Select b j s) s = j.`

However, as often with formalization, it requires a bit of work and try-and-error to find out the right definitions and the right lemmas to put in the theory of `rank` and `select`. For example, how appealing the definition of `Select` above may be, proving its equivalence with a functional version such as

² This is actually the definition that appears in Wikipedia at the time of this writing.

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```
Fixpoint select i (s : seq T) : nat :=
  if i is i.+1 then
    if s is a :: s' then (if a == b then select i s' else select i.+1 s').+1
    else 1
  else 0.
```

104 turns out to add much comfort to the development of related lemmas.

105 As a consequence, the resulting theory of `rank` and `select` sometimes looks technical and
106 we therefore refer the reader to the source code [2] to better appreciate its current status.
107 Here, we just provide for the sake of completeness the definition of two derived functions
108 that are used later in this paper.

109 2.3.1 The succ and pred functions

110 In a bitstring, the `succ` function computes the position of the next 0-bit or 1-bit. It will find
111 its use when dealing with LOUDS operations in Sect. 3.2.2. More precisely, given a bitstring
112 `s`, `succ b s y` returns the index of the next `b` following index `y`. This operation is achieved
113 by a combination of `rank` and `select`. First, a call to `rank` counts the number of `b`'s up to
114 index `y`; let N be this number. Second, a call to `select` searches for the $(N+1)^{\text{th}}$ `b` [13, p. 89]:

```
Definition succ (b : T) (s : seq T) y := select b (rank b y.-1 s).+1 s.
```

115 In particular, there is no `b` in the set $\{s_i \mid y \leq i < \text{succ } b \text{ s } y\}$:

```
Lemma succP b n (s : n.-tuple T) (y : [1, n]) :
  b \notin \bigcup_{(i : [1, n] \mid y <= i < succ b s y)} [set tacc s i].
```

116 Conversely, the `pred` function computes the position of the previous bit and will find its
117 use in Sect. 3.2.3. It is similar to `succ`, so that we only provide its definition for reference:

```
Definition pred (b : T) (s : seq T) y := select b (rank b y s) s.
```

118 3 LOUDS formalization

119 Operationally, a LOUDS encoding consists in turning a tree into an array of bits via a
120 level-order traversal. Figure 2 provides a concrete example. The resulting array is the ordered
121 concatenation of the bit representation of each node. Each node is represented by a list of
122 bits that contains as many 1-bits as there are children and that is terminated by a 0-bit.

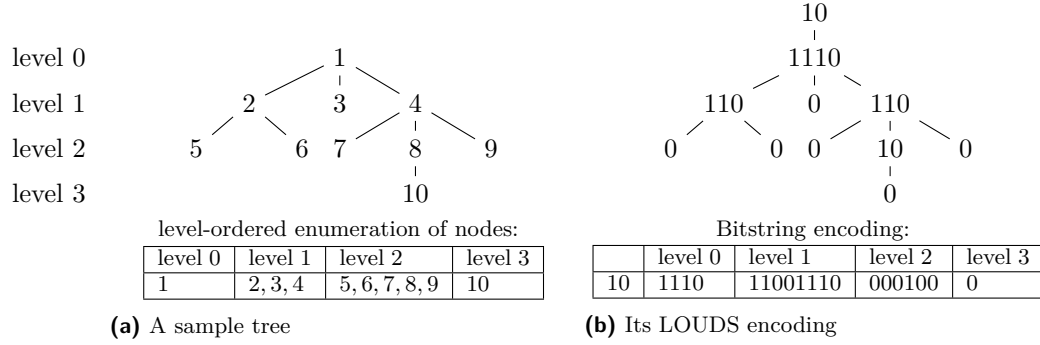
123 The significance of the LOUDS encoding is that it preserves the branching structure
124 of the tree without pointers, making for a compact representation in memory. Moreover,
125 read-only operations can be implemented using `rank` and `select`, which can be implemented
126 in constant-time.

127 We explain how we formalize the LOUDS encoding in Sect. 3.1 and how we formally
128 verify the correctness of operations on trees built out of `rank` and `select` in Sect. 3.2.

129 3.1 LOUDS encoding formalized in Coq

130 We define arbitrarily-branching trees by an inductive type:

```
Variable A : Type.
Inductive tree := Node : A -> seq tree -> tree.
Definition forest := seq tree.
Definition children_of_node : tree -> seq tree := ...
Definition children_of_forest : forest -> forest := flatten \o map children_of_node.
```



■ **Figure 2** LOUDS encoding of a sample unlabeled tree

The type **A** is for labels. We also introduce the abbreviation **forest** for a list of trees, and functions to obtain children. With this definition of trees, a leaf is a node with an empty list of children. For example, the tree of Fig. 2 becomes in COQ:

```

Definition t : tree nat := Node 1
  [:: Node 2 [:: Node 5 [::]; Node 6 [::]];
    Node 3 [::];
    Node 4 [:: Node 7 [::];
      Node 8 [:: Node 10 [::]];
      Node 9 [::]]].

```

3.1.1 Height-recursive level-order traversal

The intuitive definition of level-order traversal iterates on a forest, returning first the toplevel nodes of the forest, then their children (applying `children_of_forest`), etc. We parameterize the definition with an arbitrary function **f** for generality.

```

Variables (A B : Type) (f : tree A -> B).
Fixpoint lo_traversal' n (l : forest A) :=
  if n is n'.+1 then map f l ++ lo_traversal' n' (children_of_forest l) else [::].
Definition lo_traversal t := lo_traversal' (height t) [:: t].

```

The parameter **n** is filled here with the maximum height of the forest, meaning that we iterate just the right number of times for the forest to become empty.

Yet, this definition is not fully satisfactory. One reason is that it is not structural: we are not recursing on a tree, but iterating on a forest, using its height as recursion index. Another one is that, as we will see in Sect. 3.2, the name *level-order* is misleading. For many proofs, we are not interested in complete traversal of the tree, level by level, but rather by partial traversal along a path in the tree, where the forest we consider actually overlaps levels.

3.1.2 A structural level-order traversal

At first it may seem that the non-structurality is inherent to level-order traversal. There is no clear way to build the sequence corresponding to the traversal of a tree from those of its children. However, Gibbons and Jones [5, 8] showed that this can be achieved by splitting the output into a list of levels. One can combine two such structured traversals by *zipping* them, i.e., concatenating corresponding levels, and recover the usual traversal by flattening the list. Since concatenation of lists forms a monoid, zipping of traversals also forms a monoid.

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```

Variable (A : Type) (e : A) (M : Monoid.law e).
Fixpoint mzip (l r : seq A) : seq A := match l, r with
| (l1::ls), (r1::rs) => (M l1 r1) :: mzip ls rs
| nil, s | s, nil    => s
end.

Lemma mzipA : associative mzip.
Lemma mzip1s s : mzip [::] s = s.
Lemma mzip1s s : mzip s [::] = s.
Canonical mzip_monoid := Monoid.Law mzipA mzip1s mzip1s.

```

152 Here `Monoid.Law`, from the `bigop` module of `SSREFLECT`, denotes an operator together with
 153 its neutral element `e` and the required monoidal equations, which are also satisfied by `mzip`.

154 We now define our traversal by instantiating `mzip` to the concatenation monoid.

```

Variables (A : eqType) (B : Type) (f : tree A -> B).
Definition mzip_cat := mzip_monoid (cat_monoid B).

Fixpoint level_traversal t :=
  [:: f t] :: foldr (mzip_cat \o level_traversal) nil (children_of_node t).

Lemma level_traversal_big_eq t :
  level_traversal t =
  [:: f t] :: \big[mzip_cat/nil]_ (i <- children_of_node t) level_traversal i.

Definition lo_traversal_st t := flatten (level_traversal t).
Theorem lo_traversal_st_ok t : lo_traversal f t = lo_traversal_st t.

```

155 To let COQ recognize the structural recursion, we have to use the recursor `foldr` in
 156 the definition of `level_traversal`. Yet, the intended equation is the one expressed by
 157 `level_traversal_big_eq`, i.e., first output the image of the node, and then combine the traversals
 158 of the children. Then `lo_traversal_st` can be proved equal to the previously defined
 159 `lo_traversal`. Deforestation can furthermore improve the efficiency of `level_traversal`.

160 3.1.3 LOUDS encoding

161 Finally, the LOUDS encoding is obtained by instantiating `lo_traversal_st` with an appropriate
 162 function (called the *node description* of a node), and flattening once more:

```

Definition node_description l := rcons (nseq (size l) true) false.
Definition children_description t := node_description (children_of_node t).
Definition LOUDS t := flatten (lo_traversal_st children_description t).

```

163 Note that we chose here not to add the usual “10” prefix [13, p. 212] shown in Fig. 2, as it
 164 appeared to just complicate definitions. It can be easily recovered by adding an extra root
 165 node, as “10” is the representation of a node with 1 child.

166 For example, we can recover the encoding displayed in Fig. 2 with this definition of LOUDS:

```

Lemma LOUDS_t : LOUDS (Node 0 [:: t]) =
  [:: true; false; true; true; true; false;
   true; true; false; false; true; true; true; false;
   false; false; false; true; false; false; false].

```

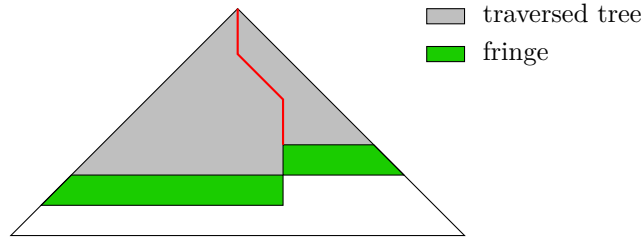
167 We can also prove some properties of this representation, such as its size:

```

Lemma size_LOUDS t : size (LOUDS t) = (number_of_nodes t).*2.-1.

```

168 This is an easy induction, remarking that `size \o flatten \o flatten` is a morphism between
 169 `mzip_cat` and `+`.



■ **Figure 3** Level-order traversal of a tree up to a path

3.2 LOUDS functions using rank and select

In this section, we formalize LOUDS functions and prove their correctness. These functions are essentially built out of `rank` and `select`. Their correctness statements establish a correspondence between operations on trees defined inductively and operations on their LOUDS encoding. We start by explaining how we represent positions in trees and then comment on the formal verification of LOUDS operations using representative examples.

3.2.1 Positions in trees

For a tree defined inductively, we represent the position of a node as usual: using a *path*, i.e., a list that records the branches taken from the root to reach the node. For example, the position of the node 8 in Fig. 2a is `[:: 2; 1]`. Not all positions are valid; we sort out the valid ones by means of the predicate `valid_position` (definition omitted for brevity).

In contrast, the position of nodes in the LOUDS encoding is not immediate. We define it as the length of the generated LOUDS up to the corresponding path. To do that, we first need to define a notion of level-order traversal up to a path, which collects all the nodes preceding the one referred by that path (which need not be valid):

```

Variables (A : eqType) (B : Type) (f : tree A -> B).
Fixpoint lo_traversal_lt (w : forest A) (p : seq nat) : seq B := match p, w with
  | nil, _ | _, nil => nil
  | n :: p', t :: w' =>
    let cl := children_of_node t in
    map f (w ++ take n cl) ++
    lo_traversal_lt (drop n cl ++ children_of_forest (w' ++ take n cl)) p'
end.

```

This new traversal appears to be the key to clean proofs of LOUDS properties. In a previous attempt using the height-recursive level-order traversal of Sect. 3.1.1, proofs were unwieldy (one needed to manually set up inductions) and lemmas did not arise naturally. We expect this new traversal to have applications to other uses of level-order traversal.

This definition may seem scary, but it closely corresponds to the imperative version of level-order traversal, which relies on a queue: to get the next node, take it from the front of the queue, and add its children to the back of the queue. We define our traversal so that the node we have reached is the one at the front of the queue `w`. To move to its n^{th} child (indices starting from 0), we first output all the nodes in the queue, and its children up to the previous one, and proceed with a new queue containing the remaining children (starting from the n^{th}) and the children of the other nodes we have just output. Figure 3 shows how the traversal progresses. The point is that as soon as the queue spans all the fringe of the traversed tree, it is able to generate the remainder of the traversal. We can verify

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198 that `lo_traversal_lt` indeed qualifies as a level-order traversal by proving that its output
199 converges to the full level-order traversal when the length of `p` reaches the height of the tree:

```
Theorem lo_traversal_lt_ok t p :  
  size p >= height t -> lo_traversal_st f t = lo_traversal_lt [:: t] p.
```

200 We also introduce a function that computes the fringe of the traversal up to `p`, i.e., the forest
201 generating the remainder of the traversal.

```
Fixpoint lo_fringe (w : forest A) (p : seq nat) : forest A := ...  
Lemma lo_traversal_lt_cat w p1 p2 :  
  lo_traversal_lt w (p1 ++ p2) =  
  lo_traversal_lt w p1 ++ lo_traversal_lt (lo_fringe w p1) p2.
```

202 We omit the definition but the lemma states exactly this property. It decomposes the traversal
203 generated by a path, allowing induction from either end of the list representing the position.

204 Using the path-indexed traversal function, we can directly obtain the index of a node in
205 the level-order traversal of a tree:

```
Definition lo_index w p := size (lo_traversal_lt id w p).
```

206 `lo_index [:: t] p` counts the number of nodes in the traversal of `t` before the position `p`.
207 Similarly, we give an alternative definition of the LOUDS encoding, and use it to map
208 a position in the tree to a position in its encoding (i.e., the index of the first bit of the
209 representation of a node):

```
Definition LOUDS_lt w p := flatten (lo_traversal_lt (@children_description A) w p).  
Definition LOUDS_position w p := size (LOUDS_lt w p).
```

210 Here the position in the whole tree is obtained as `LOUDS_position [:: t] p`, but we can also
211 compute relative positions by using `LOUDS_position w p` where `w` is a generating forest whose
212 front node is the one we start from. Note that both `lo_index` and `LOUDS_position` return
213 indices starting from 0.

214 For example, in Fig. 2, the position of the node 8 is `[:: 2; 1]` in the inductively defined
215 tree and 17 in the LOUDS encoding:

```
Definition p8 := [:: 2; 1].  
Eval compute in LOUDS_position [:: Node 0 [:: t]] (0 :: p8). (* 17 *)
```

216 Finally, here is one of the essential lemmas for proofs on LOUDS, which relates `lo_index`
217 and `LOUDS_position` using `select`:

```
Lemma LOUDS_position_select w p p' : valid_position (head dummy w) p ->  
  LOUDS_position w p = select false (lo_index w p) (LOUDS_lt w (p ++ p')).
```

218 Namely if the index of `p` is n , then its position in the LOUDS encoding is the index of its
219 n^{th} 0-bit (recall that `select` counts indices starting from 1). Here `p'` allows us to complete `p`
220 to a path of sufficient length, so that `LOUDS_lt` converges to LOUDS.

221 3.2.2 Number of children using succ

222 As a first example, let us formalize the LOUDS function that counts the number of children
223 of a node. For a tree defined inductively, this operation can be achieved by first walking
224 down the path to the node and then looking at the list of its children.


```

Fixpoint subtree (t : tree) (p : seq nat) :=
  if p is n :: p' then subtree (nth t (children_of_node t) n) p' else t.
Definition children t p := size (children_of_node (subtree t p)).

```

225 To count the number of children of a node using a LOUDS encoding, one first has to
 226 notice that each node is terminated by a 0-bit. Given such a 0-bit (or equivalently the
 227 corresponding node), one can find the number of children by computing the distance with
 228 the next 0-bit [13, p. 214]. Finding this bit is the purpose of the `succ` function of Sect. 2.3.1:

```

Definition LOUDS_children (B : bitseq) (v : nat) : nat := succ false B v.+1 - v.+1.

```

229 The `.+1` offset comes from the fact `succ` computes on indices starting from 1.

230 LOUDS_children is correct because, when applied to the LOUDS_position of a position `p`, it
 231 produces the same result as the function `children`:

```

Theorem LOUDS_childrenE (t : tree A) (p p' : seq nat) :
  let B := LOUDS_lt [:: t] (p ++ 0 :: p') in
  valid_position t p -> children t p = LOUDS_children B (LOUDS_position [:: t] p).

```

232 3.2.3 Parent and child node using rank and select

233 A path in a tree defined inductively gives direct ancestry information. In particular, removing
 234 the last index denotes the parent, and adding an extra index denotes the corresponding
 235 child. It takes more ingenuity to find parent and child using a LOUDS representation and
 236 functions from Sect. 2 alone. The idea is to count the number of nodes and branches up to
 237 the position in question [13, p. 215]. More precisely, given a LOUDS position `v`, let `Nv` be the
 238 number of nodes up to `v` (`rank false v B` computes this number). Then, `select true Nv B`
 239 looks for the `Nv`-th down-branch, which is the branch leading to the node of position `v`. Last,
 240 this branch belongs to a node whose position can be recovered using the `pred` function (from
 241 Sect. 2.3.1). Reciprocally, one computes the i^{th} child by using `rank true` and `select false`.
 242 This leads to the following definitions:

```

Definition LOUDS_parent (B : bitseq) (v : nat) : nat :=
  let j := select true (rank false v B) B in pred false B j.
Definition LOUDS_child (B : bitseq) (v i : nat) : nat :=
  select false (rank true (v + i) B).+1 B.

```

243 One can check the correctness of LOUDS_parent and LOUDS_child as follows. Consider a node
 244 reached by the path `rcons p i`. Its parent is the node reached by the path `p`, and conversely it
 245 is the i^{th} child of this node. We can formally prove that the LOUDS position of `p` (respectively
 246 `rcons p i`) and the position computed by LOUDS_parent (respectively LOUDS_child) coincide:

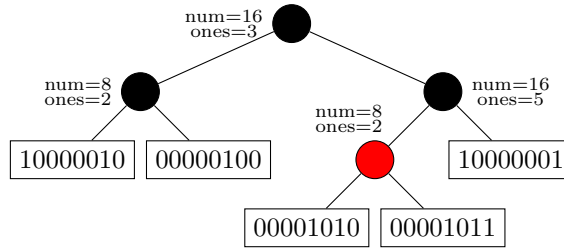
```

Variables (t : tree A) (p p' : seq nat) (i : nat).
Hypothesis HV : valid_position t (rcons p i).
Let B := LOUDS_lt [:: t] (rcons p i ++ p').
Theorem LOUDS_parentE :
  LOUDS_parent B (LOUDS_position [:: t] (rcons p i)) = LOUDS_position [:: t] p.
Theorem LOUDS_childE :
  LOUDS_child B (LOUDS_position [:: t] p) i = LOUDS_position [:: t] (rcons p i).

```

247 The approach that we explained so far shows how to carry out the formal verification of
 248 the LOUDS operations that are listed in [13, Table 8.1]. However, how useful they may be
 249 for many big-data applications, these operations assume static compact data structures. The
 250 next section explains how to extend our approach to deal with dynamic structures.

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■ **Figure 4** Example of tree representation of a dynamic bit vector

4 Dynamic bit vectors

In some applications bit vectors need to support dynamic operations—not just static queries. We formalize such *dynamic bit vectors*, and implement and verify “dynamic operations” on them: inserting a bit into a bit vector, and deleting a bit from one.

In Sect. 4.1, we explain the data structure that allows for an efficient implementation of dynamic operations. In Sect. 4.2, we formalize the **rank** and **select** queries. Sections 4.3 and 4.4 are dedicated to the formalization of the more difficult insertion and deletion.

4.1 Representing dynamic bit vectors

The choice of representation for dynamic bit vectors is motivated by complexity considerations. Insertion into a linear array has time complexity $O(n)$, but we can improve this by using a balanced binary search tree to represent the bit array, which enables us to handle insertions in $\max(O(w), O(\log n))$ time, with a trade-off of $O(n/w)$ bits of extra space, where w is a parameter controlling the width of each tree node [13].

In our formalization of the dynamic bit vector’s algorithms, we use a red-black tree as our balanced tree structure. Each node holds a color and meta-data about the bit vector, and each leaf holds a *flat* (i.e., list-based) bit array. We store two natural numbers in each node: the size and the rank of the left subtree (recorded as “num” and “ones” in Fig. 4).

```

Inductive color := Red | Black.
Inductive btree (D A : Type) : Type :=
| Bnode of color & btree D A & D & btree D A
| Bleaf of A.

Definition dtree := btree (nat * nat) (seq bool).

```

Our first step is to formalize the structural invariant of our tree representation of bit vectors, which is required to prove the correctness of queries and updates on it. It states that the numbers encoded in each node are the left child’s size and rank, and that leaves contain a number of bits between **low** and **high**.

```

Variables low high : nat. (* instantiated as (w ^ 2) ./ 2 and (w ^ 2) .* 2 *)
Fixpoint wf_dtree (B : dtree) := match B with
| Bnode _ l (num, ones) r => [ && num == size (dflatten l),
                              ones == count_mem true (dflatten l),
                              wf_dtree l & wf_dtree r ]
| Bleaf arr                => low <= size arr < high
end.

```

Here, the function `dflatten` defines the semantics of our tree representation of a bit vector (`dtree`) by converting it to a flat representation of that vector:

```
Fixpoint dflatten (B : dtree) := match B with
| Bnode _ l _ r => dflatten l ++ dflatten r
| Bleaf s => s
end.
```

4.2 Verifying basic queries

The basic query operations can be easily defined via traversal of the tree. We implement the queries `rank`, `select1`, and `select0` as the COQ functions `drank`, `dselect1`, and `dselect0`. For example, `drank` is implemented as follows, using the (static) `rank` function from Sect. 2.1:

```
Fixpoint drank (B : dtree) (i : nat) := match B with
| Bnode _ l (num, ones) r =>
  if i < num then drank l i else ones + drank r (i - num)
| Bleaf s => rank true i s
end.
```

We prove that our function `drank` indeed computes the query `rank` using a custom induction principle `dtree_ind`, corresponding to the predicate `wf_dtree`:

```
Lemma drankE (B : dtree) i : wf_dtree B -> drank B i = rank true i (dflatten B).
Proof. move=> wf; move: B wf i. apply: dtree_ind. (* ... *) Qed.
```

Note that our implementation is only correct on well-formed trees.

The formalization and verification of the `select` queries proceed along the same lines.

4.3 Implementing and verifying insertion

Insertion is significantly harder to implement than static queries. We need to maintain the invariant on the size of the leaves, which means that we have to split a leaf if it becomes too big, and in that case we may need to rebalance the tree, to maintain the red-black invariant, updating the meta-data on the way.

We translate the algorithm given by Navarro [13] directly into COQ:

```
Definition dins_leaf s b i :=
  let s' := insert1 s b i in (* insert element b in sequence s at position i *)
  if size s + 1 == high then
    let n := size s' % 2 in let sl := take n s' in let sr := drop n s' in
    Bnode Red (Bleaf _ sl) (n, count_mem true sl) (Bleaf _ sr)
  else Bleaf _ s'.

Fixpoint dins (B : dtree) b i : dtree := match B with
| Bleaf s => dins_leaf s b i
| Bnode c l d r =>
  if i < d.1 then balanceL c (dins l b i) r (d.1+1, d.2 + b)
  else balanceR c l (dins r b (i - d.1)) d
end.

Definition dininsert (B : btree D A) b i : btree D A :=
  match dins B b i with
| Bleaf s => Bleaf _ s
| Bnode _ l d r => Bnode Black l d r
end.
```

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`dins` recurses on the tree, searching for the leaf where the insertion must be done, calling then `dins_leaf`, which inserts a bit in the leaf, eventually splitting it if required. On its way back, `dins` calls balancing functions `balanceL` and `balanceR` to maintain the red-black invariant. We omit the code of the balancing functions (see [2]). Like the standard version, they fix imbalances possibly occurring on the left and on the right, respectively, but they must also adjust the meta-data in the nodes. `dinsert` is a simple wrapper over `dins` that completes the insertion by painting the root black. The real definitions are more abstract [2]; we chose to instantiate them in this paper for readability.

Verifying `dinsert` requires verifying three different properties: `dinsert` must (a) preserve the data, (b) maintain the structural invariants of the tree, and (c) return a balanced red-black tree. Properties (a) and (b) are related, in that the latter is required by the former.

Notation `wf_dtree_l` := (`wf_dtree` low high).

Definition `wf_dtree' t` := `if t is Bleaf s then size s < high else wf_dtree_l t`.

Lemma `wf_dtree_dtree' t` : `wf_dtree_l t -> wf_dtree' t`.

Lemma `wf_dtree'_dtree t` : `wf_dtree' t -> wf_dtree 0 high t`.

Lemma `dinsertE (B : dtree) b i w` :

`wf_dtree' B -> dflatten (dinsert B b i) = insert1 (dflatten B) b i`.

Lemma `dinsert_wf (B : dtree) b i` : `wf_dtree' B -> wf_dtree' (dinsert B b i)`.

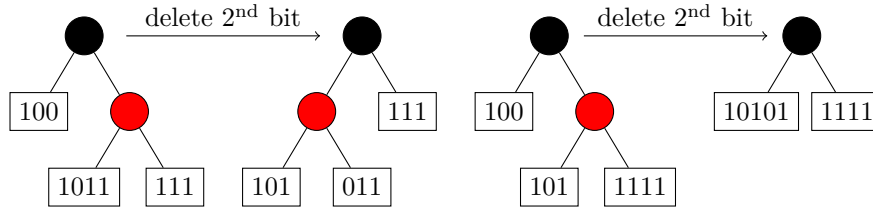
A subtle point here is that we may start from a tree formed of a single small leaf, i.e., a leaf smaller than `low`. To handle this situation we introduce `wf_dtree'`, which does not enforce the lower bound on this single leaf. This new predicate is entailed by the original invariant (it removes one check), but interestingly it also entails it if we set the lower bound to 0. Since the queries of Sect. 4.2 were proved with abstract lower and upper bounds, their proofs are readily usable through this weakening. However, we need to use `wf_dtree'` when we prove properties of `dinsert`, as it modifies the tree.

Proving (a) and (b) involves no theoretical difficulty. We explain in Sect. 5 some techniques to write short proofs: about 100 lines in total for both properties, including lemmas for `balanceL` and `balanceR`, which involve large case analyses.

Property (c) about `dinsert` never breaking the red-black tree invariant is notoriously more challenging. More importantly, we want to eliminate cases where the “height balance” at a node is broken. It is easy to model the property that no red node has a red child; the “height balance” property is modeled using the black-depth. We can thus model the red-black tree invariant with a recursive function that takes as arguments the “color context” `ctxt` (the color of the parent’s node) and the black-depth of the node `bh`:

```
Fixpoint is_redblack (B : dtree) (ctxt : color) (bh : nat) := match B with
| Bleaf _ => bh == 0
| Bnode c l _ r => match c, ctxt with
| Red, Red   => false
| Red, Black => is_redblack l Red bh && is_redblack r Red bh
| Black, _   => (bh > 0) && is_redblack l Black bh.-1
               && is_redblack r Black bh.-1
end end.
```

To show that `dinsert` preserves the red-black tree property, we define and prove a number of weaker structural lemmas that are basically equivalent to stating that a tree returned by `dins` is structurally valid if the root is painted black. We do not describe the proof in detail because the technique is well-known [15] and has been formalized in multiple sources [3, 4]. Using these weaker lemmas, we can prove the following structural validity lemma:



■ **Figure 5** Base cases of delete (lower bound = 3)

Lemma `dinsert_is_redblack` ($B : \text{dtree}$) $b\ i\ n :$
`is_redblack B Red n` \rightarrow `exists n', is_redblack (dinsert B b i) Red n'`.

4.4 Deletion: searching for invariants

Deletion in dynamic bit vectors is difficult for two reasons. One is that, in order to maintain the upper and lower bounds on the size of leaves, which is required to attain simultaneously space and time efficiency, deleting a bit in a leaf may require some rearrangement of the surrounding nodes. Figure 5 shows the result of deleting a bit in a leaf of the tree, when this leaf has already the smallest allowed size. This can be resolved by borrowing a bit from a sibling (left case), or merging two siblings (right case), but depending on the configurations of nodes, this may require to first rotate the tree.

The other is that deletion in a functional red-black tree is a complex operation [9], and that finding how to adapt the invariants of the literature to our specific case proved to be non-trivial. Therefore, we took a twofold approach. First, we searched for invariants in a concrete tree structure with invariants encoded using dependent types. Then, we removed dependent types and implemented `delete` and proved its correctness (more details in Sect. 5).

Contrary to insertion, knowing the color of the modified child is not sufficient to rebalance its parent correctly after deletion, and recompute its meta-data. We need to propagate two more pieces of information: whether the black-height decreased (`d_down` below), and the meta-data corresponding to the deleted bit (`d_del`). We encapsulate these in a “tree state”:

Record `deleted_dtree`: `Type` := `MkD { d_tree :> dtree; d_down: bool; d_del: nat*nat }`.

Definition `is_nearly_redblack'` $tr\ (c : \text{color})\ (bh : \text{nat}) :=$
`if d_down tr then is_redblack tr Red bh.-1 else is_redblack tr c bh.`

Note that `deleted_dtree` is automatically coerced to `dtree`.

Now, we can define `delete` in the natural way, but we need to take care about balance operations and invariants on the size of leaves. Specifically, the balance operations must be reimplemented as `balanceL'` and `balanceR'`, which need to satisfy the following invariants.

Definition `balanceL'` ($c:\text{color}$) ($l:\text{deleted_dtree}$) ($d:\text{nat}*\text{nat}$) ($r:\text{dtree}$):`deleted_dtree` :=
Definition `balanceR'` ($c:\text{color}$) ($l:\text{dtree}$) ($d:\text{nat}*\text{nat}$) ($r:\text{deleted_dtree}$):`deleted_dtree` :=

Lemma `balanceL'_Black_nearly_is_redblack` $l\ r\ n\ c :$
 $0 < n \rightarrow \text{is_nearly_redblack}'\ l\ \text{Black}\ n.-1 \rightarrow \text{is_redblack}\ r\ \text{Black}\ n.-1 \rightarrow$
 $\text{is_nearly_redblack}'\ (\text{balanceL}'\ \text{Black}\ l\ r)\ c\ n.$
Lemma `balanceL'_Red_nearly_is_redblack` $l\ r\ n :$
 $\text{is_nearly_redblack}'\ l\ \text{Red}\ n \rightarrow \text{is_redblack}\ r\ \text{Red}\ n \rightarrow$
 $\text{is_nearly_redblack}'\ (\text{balanceL}'\ \text{Red}\ l\ r)\ \text{Black}\ n.$
(similar statements with respect to balanceR' *)*

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Regarding leaves, we need special processing in the base cases of `delete`, as illustrated in Fig. 5. `delete` might have to “borrow” a bit from a sibling of a target leaf or combine target siblings (possibly after a rotation), to preserve the size invariants. Afterwards, `delete` will recursively rebalance the whole `dtree`.

Thus we implement `delete` (as `ddel`), and prove its correctness as follows:

```
Fixpoint ddel (B : dtree) (i : nat) : deleted_dtree := ...

Lemma ddeleteE B i : wf_dtree' B -> dflatten (ddel B i) = delete (dflatten B) i.
Lemma ddelete_wf (B : dtree) n i :
  is_redblack B Black n -> i < dsize B -> wf_dtree' B -> wf_dtree' (ddel B i).
Lemma ddelete_is_redblack B i n :
  is_redblack B Red n -> exists n', is_redblack (ddel B i) Red n'.
```

These statements are variants of the properties (a), (b) and (c) of Sect. 4.3. The proofs are complicated by the huge number of cases, handled using the proof techniques discussed in the next section.

5 Using small-scale reflection with inductive data

The small-scale reflection approach is known to be beneficial for mathematical proofs [11]. However, while SSREFLECT tactics are now widely used in the COQ community, it is not always clear how to write proofs of programs using inductive data structures in an idiomatic style, in particular in presence of deep case analysis.

In the first part of the paper, concerning level-order traversal, the question is not so acute, as the induction principle we need for LOUDS is not structural on the shape of trees, but rather on paths, represented as lists, which are already well supported by the SSREFLECT library. Thus the question was the more traditional one of which definitions to use, so that we can obtain natural lemmas. This proved to be a time consuming process, which led to gradually build a library of lemmas, resulting in proofs that match the intuition, using almost only case analysis and rewriting.

However, the second part, about dynamic bit vectors, uses heavily structural induction on binary trees, and required developing some proof techniques to streamline the proofs.

A basic idea of small-scale reflection is to use recursive boolean predicates (i.e., recursive computable functions) rather than inductive propositions. We have already presented two examples: `wf_dtree` and `is_redblack`. Properly designed, they allow one to prune case analysis by reducing to `false` on impossible cases. On the other hand, they do not decompose naturally in inductive proofs, which led us first to apply a standard technique: define a specialized induction principle for trees satisfying `wf_dtree` (`dtree_ind` in Sect. 4.2). Using it, the correctness of static queries and non-structural modification operations (i.e., setting and clearing of bits) were easy to prove, as the case analysis was trivial.

Properties of `dinsert`, `ddel`, and their auxiliary functions are trickier to prove, as they require complex case analyses and delicate re-balancing of branches. Nevertheless, we essentially applied the same principle of crushing goals (in the style of [4]) through direct case analysis. With this approach, the correctness lemmas (which state that our operations are semantically correct) were largely automated, consistent with prior research [14]. The structural lemmas were harder to prove, mainly due to the sheer number of cases involved and the complexity of invariants. Our proofs proceed by first applying case analysis to the tree up to the required depth, and then decomposing all assumptions to repeatedly rewrite the goal using them until it is solved. This proof pattern is captured by the following tactic:

Contents (Section in <code>dynamic_redblack.v</code>)	Lines of code	Lines of proof
Definitions (<code>btree</code> , <code>dtree</code>)	19	18
Queries (<code>dtree</code>)	38	58
Insertion (<code>insert</code> , <code>dinsert</code>)	65	208
Set/clear a bit (<code>set_clear</code>)	25	152
Deletion (<code>delete</code> , <code>ddelete</code>)	98	215

■ **Table 1** Implementation of dynamic bit vectors (see Table 2 for the whole implementation)

File in [2]	Section in this paper
<code>rank_select.v</code>	Sections 2.1, 2.2, 2.3
<code>pred_succ.v</code>	Sect. 2.3.1
<code>compact_data_structures.v</code>	Sections 3.1.1, 3.1.2
<code>loads.v</code>	Sections 3.1.3, 3.2
<code>dynamic_redblack.v</code>	Sect. 4

■ **Table 2** Formalization overview [2] (see Table 1 for the details about dynamic bit vectors)

```

Ltac decompose_rewrite :=
  let H := fresh "H" in
  move/andP => [] || (move => H; try rewrite H; try rewrite (eqP H)).

```

It is reminiscent of the `intuition` tactic, a generic tactic for intuitionistic logic which breaks both hypotheses and goals into pieces; here we rather rely on rewriting inside boolean conjunctions to solve goals piecewise. For `dinsert`, this approach instantly finishes most of our proofs, especially those about red-black tree invariants; the few cases that require manual treatment being usually handled in one single `rewrite`. This is true for most auxiliary functions of `ddel` too, with one caveat: where `dinsert` has us generate a dozen cases, `ddel` requires hundreds. To cope with this, we had first to decompose the case analysis in steps, solving most cases on the way, which means losing some simplicity to speed up proof search. The proof is still mostly automatic: apply `decompose_rewrite`, and throw in relevant lemmas. When possible, it appears that using `apply` instead of `rewrite` speeds up by a factor of 2 or more, which matters when the lemma takes more than 1 minute to prove. We have only 3 such time-consuming case analyses, one for each invariant. Among the 12 lemmas involved in proving the invariants, only the inductive proof of well-formedness for `ddel` seems to show the limit of this approach, as it required specific handling for each case of the function definition.

For comparison, Table 1 provides the size of code and proof required for each Section of our proof script. This does not include lemmas about the list-based reference implementation. Note that we count all boolean predicates used to model properties as proofs.

Last, we mention our experience with alternative approaches. In parallel with our development using small-scale reflection, we attempted to formalize dynamic bit vectors using dependent types, where all invariants are encoded in the type of the data itself. While this guarantees that we never forget an invariant, difficulties with the `Program` [19] environment led us to write some functions using tactics [2, `dynamic_dependent_tactic.v`]. As written in Sect. 4.4, this direct connection between code and proof actually helped us discover some tricky invariants. However, the resulting code does not lend itself to further analysis, hence our choice here to stick to a more conventional separation between code and proof. We did eventually succeed in re-implementing the dependently-typed version using the `Program` environment, but at the price of very verbose definitions [2, `dynamic_dependent_program.v`].

407 6 Related work

408 CoQ has been used to formalize a constant-time, $o(n)$ -space rank function that was further-
 409 more extracted to efficient OCaml code [20] and C code [21]. This work focuses on the rank
 410 query for static bit arrays while our work extends the toolset for succinct data structures
 411 with more queries (`select`, `succ`, etc.) and dynamic structures.

412 The functions `level_traversal` and `lo_traversal_st` of Sect. 3.1.2 match functions given
 413 in squiggle notation in related work by Jones and Gibbons [8]. In this work, the `mzip` function
 414 of Sect. 3.1.2 also appears and is called “long zip with plussle”. To the best of our knowledge,
 415 the function `lo_traversal_lt` is original to our work.

416 One may use any kind of balanced binary tree to represent dynamic bit vectors [13].
 417 There are many purely-functional balanced binary search trees, such as AVL trees [12] and
 418 Adams trees [1], but purely functional red-black trees [15, 9] are the most widely studied. As
 419 a matter of fact, they have already been formalized in CoQ [3, 4], Agda [16], and Isabelle [14].

420 We had to re-implement red-black trees due to the difference of stored contents. Above
 421 CoQ formalizations are intended to represent sets, and maintain the ordering invariant. Our
 422 trees represent vectors, and maintain both that the contents (as concatenation of the leaves)
 423 are unchanged, and that meta-data in inner nodes is correct (see Sect. 4.1). Still, we found
 424 many hints in related work. For example, in Sect. 4.3 about insertion, the balancing functions
 425 use Okasaki’s well-known purely functional balance algorithm [15], and we formulate our
 426 invariants and propositions similarly to above CoQ formalizations.

427 There are now many proofs of programs that use SSREFLECT, but we could not find
 428 much discussion trying to synthesize the new techniques put at work. Sergey et al. used
 429 SSREFLECT for teaching [17, 18], observing benefits for clarity and maintainability, but
 430 also giving examples of custom tactics needed to prove programs. Gonthier et al. [7] have
 431 shown how, in some cases, one can avoid relying on ad hoc tactics through an advanced
 432 technique involving overloading of lemmas. The techniques we describe in Sect. 5, while
 433 more rudimentary, are simple and efficient, yet we have not seen them described elsewhere.

434 7 Conclusion

435 We reported on an effort to formalize succinct data structures. We started with a foundational
 436 theory of the rank and select functions for counting and searching bits in immutable arrays.
 437 Using this theory, we formalized a standard compact representation of trees (LOUDS) and
 438 proved the correctness of its basic operations. Last, we formalized dynamic bit vectors: an
 439 advanced topic in succinct data structures.

440 Our work is a first step towards the construction of a formal theory of succinct data
 441 structures. We already overcame several technical difficulties while dealing with LOUDS
 442 trees: it took much care to find suitable recursive traversals and to sort out the off-by-one
 443 conditions when specifying basic operations. Similarly, the formalization of dynamic vectors
 444 could not be reduced to the matter of extending conservatively an existing formalization of
 445 balanced trees: we needed to re-implement them to accommodate specific invariants.

446 As for future work, we plan to enable code extraction for the functions we have been
 447 verifying, and prove their complexity, so as to complete previous work [20] and ultimately
 448 achieve a formally verified implementation of succinct data structures. We have already
 449 shown that the LOUDS representation of a tree with n nodes uses just $2n$ bits of data. For
 450 the LOUDS operations, constant time complexity is a direct consequence of their being
 451 implemented using a constant number of rank and select operations. For dynamic bit vectors,
 452 we will first need to properly define a framework for space and time complexity.

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