Computing the 4-Edge-Connected Components of a Graph in Linear Time

Loukas Georgiadis, Giuseppe F Italiano, Evangelos Kosinas

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Loukas Georgiadis[1] Giuseppe F. Italiano[2] Evangelos Kosinas[3]

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Abstract

We present the first linear-time algorithm that computes the 4-edge-connected components of an undirected graph. Hence, we also obtain the first linear-time algorithm for testing 4-edge connectivity. Our results are based on a linear-time algorithm that computes the 3-edge cuts of a 3-edge-connected graph G, and a linear-time procedure that, given the collection of all 3-edge cuts, partitions the vertices of G into the 4-edge-connected components.

1 Introduction

Let $G = (V, E)$ be a connected undirected graph with m edges and n vertices. An *(edge) cut* of G is a set of edges $S \subseteq E$ such that $G \setminus S$ is not connected. We say that S is a k*-cut* if its cardinality is $|S| = k$. Also, we refer to the 1-cuts as the *bridges* of G. A cut S is *minimal* if no proper subset of S is a cut of G. The *edge connectivity* of G, denoted by $\lambda(G)$, is the minimum cardinality of an edge cut of G. A graph is k*-edge-connected* if $\lambda(G) \geq k$.

A cut S separates two vertices u and v, if u and v lie in different connected components of $G \setminus S$. Vertices u and v are k-edge-connected, denoted by $u \overset{G}{\equiv}_k v$, if there is no $(k-1)$-cut that separates them. By Menger's theorem [15], u and v are k-edge-connected if and only if there are k-edge-disjoint paths between u and v. A k*-edge-connected component* of G is a maximal set $C \subseteq V$ such that there is no $(k-1)$-edge cut in G that disconnects any two vertices $u, v \in C$ (i.e., u and v are in the same connected component of $G \setminus S$ for any $(k-1)$-edge cut S). We can define, analogously, the *vertex cuts* and the k*-vertex-connected components* of G.

Computing and testing the edge connectivity of a graph, as well as its k-edge-connected components, is a classical subject in graph theory, as it is an important notion in several application areas (see, e.g., [17]), that has been extensively studied since the 1970's. It is known how to compute the $(k-1)$-edge cuts, $(k-1)$-vertex cuts, k-edge-connected components and k-vertex-connected components of a graph in linear time for $k \in \{2, 3\}$ [5, 9, 16, 19, 22]. The case $k = 4$

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[1]Department of Computer Science & Engineering, University of Ioannina, Greece. E-mail: loukas@cs.uoi.gr

[2]LUISS University, Rome, Italy. E-mail: gitaliano@luiss.it

[3]Department of Computer Science & Engineering, University of Ioannina, Greece. E-mail: ekosinas@cs.uoi.gr

has also received significant attention [2, 3, 10, 11]. Unfortunately, none of the previous algorithms achieved linear running time. In particular, Kanevsky and Ramachandran [10] showed how to test whether a graph is 4-vertex-connected in $O(n^2)$ time. Furthermore, Kanevsky et al. [11] gave an $O(m + n\alpha(m,n))$-time algorithm to compute the 4-vertex-connected components of a 3-vertex-connected graph, where α is a functional inverse of Ackermann's function [21]. Using the reduction of Galil and Italiano [5] from edge connectivity to vertex connectivity, the same bounds can be obtained for 4-edge connectivity. Specifically, one can test whether a graph is 4-edge-connected in $O(n^2)$ time, and one can compute the 4-edge-connected components of a 3-edge-connected graph in $O(m + n\alpha(m,n))$ time. Dinitz and Westbrook [3] presented an $O(m + n \log n)$-time algorithm to compute the 4-edge-connected components of a general graph G (i.e., when G is not necessarily 3-edge-connected). Nagamochi and Watanabe [18] gave an $O(m+k^2n^2)$-time algorithm to compute the k-edge-connected components of a graph G, for any integer k. We also note that the edge connectivity of a simple undirected graph can be computed in $O(m\text{polylog}n)$ time, randomized [7, 12] or deterministic [8, 14]. The best current bound is $O(m \log^2 n \log \log^2 n)$, achieved by Henzinger et al. [8] which provided an improved version of the algorithm of Kawarabayashi and Thorup [14].

Our results and techniques In this paper we present the first linear-time algorithm that computes the 4-edge-connected components of a general graph G, thus resolving a problem that remained open for more than 20 years. Hence, this also implies the first linear-time algorithm for testing 4-edge connectivity. We base our results on the following ideas. First, we extend the framework of Georgiadis and Kosinas [6] for computing 2-edge cuts (as well as mixed cuts consisting of a single vertex and a single edge) of G. Similar to known linear-time algorithms for computing 3-vertex-connected and 3-edge-connected components [9, 22], Georgiadis and Kosinas [6] define various concepts with respect to a depth-first search (DFS) spanning tree of G. We extend this framework by introducing new key parameters that can be computed efficiently and provide characterizations of the various types of 3-edge cuts that may appear in a 3-edge-connected graph. We deal with the general case by dividing G into auxiliary graphs $H_1, \dots, H_\ell$, such that each H_i is 3-edge-connected and corresponds to a different 3-edge-connected component of G. Also, for any two vertices x and y, we have $x \overset{G}{\equiv}_4 y$ if and only if x and y are both in the same auxiliary graph H_i and $x \overset{H_i}{\equiv}_4 y$. Furthermore, this reduction allows us to compute in linear time the number of *minimal* 3-*edge cuts* in a general graph G. Next, in order to compute the 4-edge-connected components in each auxiliary graph H_i, we utilize the fact that a minimum cut of a graph G separates G into two connected components. Hence, we can define the set V_C of the vertices in the connected component of $G \setminus C$ that does not contain a specified root vertex r. We refer to the number of vertices in V_C as the r-*size* of the cut C. Then, we apply a recursive algorithm that successively splits H_i into smaller graphs according to its 3-cuts. When no more splits are possible, the connected components of the final split graph correspond to the 4-edge-connected components of G. We show that we can implement this procedure in linear time by processing the cuts in non-decreasing order with respect to their r-size.

2 Concepts defined on a DFS-tree structure

Let $G = (V, E)$ be a connected undirected graph, which may have multiple edges. For a set of vertices $S \subseteq V$, the induced subgraph of S, denoted by $G[S]$, is the subgraph of G with vertex set S and edge set $\{e \in E \mid \text{both ends of } e \text{ lie in } S\}$. Let T be the spanning tree of G provided by a depth-first search (DFS) of G [19], with start vertex r. The edges in T are called tree-edges; the edges in $E \setminus T$ are called back-edges, as their endpoints have ancestor-descendant relation in T. A vertex u is an ancestor of a vertex v (v is a descendant of u) if the tree path from r to v contains u. Thus, we consider a vertex to be an ancestor (and, consequently, a descendant) of itself. We let $p(v)$ denote the parent of a vertex v in T. If u is a descendant of v in T, we denote the set of vertices of the simple tree path from u to v as $T[u, v]$. The expressions $T[u, v)$ and $T(u, v]$ have the obvious meaning (i.e., the vertex on the side of the parenthesis is excluded). From now on, we identify vertices with their preorder number (assigned during the DFS). Thus, v being an ancestor of u in T implies that $v \leq u$. Let $T(v)$ denote the set of descendants of v, and let $ND(v)$ denote the number of descendants of v (i.e. $ND(v) = |T(v)|$). With all $ND(v)$ computed, we can check in constant time whether a vertex u is a descendant of v, since $u \in T(v)$ if and only if $v \leq u$ and $u < v + ND(v)$ [20].

Whenever (x, y) denotes a back-edge, we shall assume that x is a descendant of y. We let $B(v)$ denote the set of back-edges (x, y), where x is a descendant of v and y is a proper ancestor of v. Thus, if we remove the tree-edge $(v, p(v))$, $T(v)$ remains connected to the rest of the graph through the back-edges in $B(v)$. This implies that G is 2-edge-connected if and only if $|B(v)| > 0$, for every $v \neq r$. Furthermore, G is 3-edge-connected only if $|B(v)| > 1$, for every $v \neq r$. We let $b\_count(v)$ denote the number of elements of $B(v)$ (i.e. $b\_count(v) = |B(v)|$). $low(v)$ denotes the lowest y such that there exists a back-edge $(x, y) \in B(v)$. Similarly, $high(v)$ is the highest y such that there exists a back-edge $(x, y) \in B(v)$.

We let $M(v)$ denote the nearest common ancestor of all x for which there exists a back-edge $(x, y) \in B(v)$. Note that $M(v)$ is a descendant of v. Let m be a vertex and $v_1, \dots, v_k$ be all the vertices with $M(v_1) = \dots = M(v_k) = m$, sorted in decreasing order. (Observe that v_{i+1} is an ancestor of v_i, for every $i \in \{1, \dots, k-1\}$, since m is a common descendant of all $v_1, \dots, v_k$.) Then we have $M^{-1}(m) = \{v_1, \dots, v_k\}$, and we define $nextM(v_i) := v_{i+1}$, for every $i \in \{1, \dots, k-1\}$, and $lastM(v_i) := v_k$, for every $i \in \{1, \dots, k\}$. Thus, for every vertex v, $nextM(v)$ is the successor of v in the decreasingly sorted list $M^{-1}(M(v))$, and $lastM(v)$ is the lowest element in $M^{-1}(M(v))$.

The following two simple facts have been proved in [6].

Fact 2.1. *All $ND(v)$, $b\_count(v)$, $M(v)$, $low(v)$ and $high(v)$ can be computed in total linear-time, for all vertices v.*

Fact 2.2. *$B(u) = B(v) \Leftrightarrow M(u) = M(v)$, and $high(u) = high(v) \Leftrightarrow M(u) = M(v)$ and $b\_count(u) = b\_count(v)$.*

Furthermore, [6] implies the following characterization of a 3-edge-connected graph.

Fact 2.3. *G is 3-edge-connected if and only if $|B(v)| > 1$, for every $v \neq r$, and $B(v) \neq B(u)$, for every pair of vertices u and v, $u \neq v$.*

Lemma 2.4. *Let v be an ancestor of u and $M(v)$ a descendant of u. Then, $M(v)$ is a descendant of $M(u)$.*

Proof. Let $(x, y) \in B(v)$. Then x is a descendant of $M(v)$, and therefore a descendant of u. Furthermore, y is a proper ancestor of v, and therefore a proper ancestor of u. This shows that $(x, y) \in B(u)$, and thus we have $B(v) \subseteq B(u)$. This shows that $M(v)$ is a descendant of $M(u)$. ☐

The following lemma will be implicitly evoked several times in the following sections.

Lemma 2.5. *Let u be a proper descendant of v such that $M(u) = M(v)$. Then, $B(v) \subseteq B(u)$. Furthermore, if the graph is 3-edge-connected, $B(v) \subset B(u)$.*

Proof. Let $(x, y) \in B(v)$. Then x is a descendant of $M(v)$, and therefore a descendant of $M(u)$, and therefore a descendant of u. Furthermore, y is a proper ancestor of v, and therefore a proper ancestor of u. This shows that $(x, y) \in B(u)$, and thus $B(v) \subseteq B(u)$ is established. If the graph is 3-edge-connected, $B(v) \subset B(u)$ is an immediate consequence of fact 2.3. □

Now let us provide some extensions of those concepts that will be needed for our purposes. Assume that G is 3-edge-connected, and let $v \neq r$ be a vertex of G. By fact 2.3, $b\_count(v) > 1$, and therefore there are at least two back-edges in $B(v)$. Of course, there is at least one back-edge $(x, y) \in B(v)$ such that $y = low(v)$. We let $low1(v)$ denote y, and $low1D(v)$ denote x. That is, $low1(v)$ is the *low* point of v, and $low1D(v)$ is a descendant of v which is connected with a back-edge to its *low* point. (Of course, $low1D(v)$ is not uniquely determined, but we need to have at least one such descendant stored in a variable.) Similarly, we let $highD(v)$ denote a descendant of v which is connected with a back-edge to the *high* point of v. (Again, $highD(v)$ is not uniquely determined.) Then, there may exist another back-edge $(x', y') \in B(v)$ with $x' \neq x$ and $y' = y$. In this case, we let $low2(v)$ denote y' (that is, $low2(v)$ is, again, the *low* point of v) and $low2D(v)$ denote x'. If there is no back-edge $(x', y') \in B(v)$ with $x' \neq x$ and $y' = y$, let $(x', y') \in B(v)$ denote a back-edge with $y' = min(\{w \mid \exists(z, w) \in B(v)\} \setminus \{y\})$. Then we let $low2(v)$ denote y' and $low2D(v)$ denote x'. Thus, if $v \neq r$, we know that $(low1D(v), low(v))$ and $(low2D(v), low2(v))$ are two distinct back-edges in $B(v)$. We have defined *low1*, *low1D*, *low2* and *low2D* because we need to have stored, for every vertex $v \neq r$, two back-edges from $B(v)$ (see section 3.1). Any other pair of back-edges from $B(v)$ could do as well. It is easy to compute all $low1(v)$, $low1D(v)$, $low2(v)$ and $low2D(v)$ during the DFS.

We let $l(v)$ denote the lowest y for which there exists a back-edge (v, y), or v if no such back-edge exists. Thus, $low(v) \leq l(v)$. Now let $c_1, \ldots, c_k$ be the children of v sorted in non-decreasing order w.r.t. their *low* point. Then we call c_1 the *low1* child of v, and c_2 the *low2* child of v. (Of course, the *low1* and *low2* children of v are not uniquely determined after a DFS on G, since we may have $low(c_1) = low(c_2)$.) We let $\tilde{M}(v)$ denote the nearest common ancestor of all x for which there exists a back-edge $(x, y) \in B(v)$ with x a proper descendant of $M(v)$. Formally, $\tilde{M}(v) := \text{nca}\{x \mid \exists(x, y) \in B(v) \text{ and } x \neq M(v)\}$. If the set $\{x \mid \exists(x, y) \in B(v) \text{ and } x \neq M(v)\}$ is empty, we leave $\tilde{M}(v)$ undefined. We also define $M_{low1}(v)$ as the nearest common ancestor of all x for which there exists a back-edge $(x, y) \in B(v)$ with x being a descendant of the *low1* child of $M(v)$, and $M_{low2}(v)$ as the nearest common ancestor of all x for which there exists a back-edge $(x, y) \in B(v)$ with x a descendant of the *low2* child of $M(v)$. Formally, $M_{low1}(v) := \text{nca}\{x \mid \exists(x, y) \in B(v) \text{ and } x \text{ is a descendant of the } low1 \text{ child of } M(v)\}$ and $M_{low2}(v) := \text{nca}\{x \mid \exists(x, y) \in B(v) \text{ and } x \text{ is a descendant of the } low2 \text{ child of } M(v)\}$. If the set in the formal definition of $M_{low1}(v)$ (resp. $M_{low2}(v)$) is empty, we leave $M_{low1}(v)$ (resp. $M_{low2}(v)$) undefined.

2.1 Computing the DFS parameters in linear time

Algorithm 1 shows how we can easily compute $highD(v)$ during the computation of all *high* points. The algorithm uses the static tree disjoint-set-union data structure of Gabow and Tarjan [4] to achieve linear running time.

Algorithm 2 shows how we can compute all $M(v)$ and $nextM(v)$, algorithm 3 shows how we can compute all $\tilde{M}(v)$, and algorithm 4 shows how we can compute all $M_{low1}(v)$ and $M_{low2}(v)$, for all vertices $v \neq r$, in total linear time. These algorithms process the vertices in a bottom-up fashion, and they work recursively on the descendants of a vertex. To perform these computations in linear time, we have to avoid descending to the same vertices an excessive amount of times during the recursion. To achieve this, we use a variable $currentM[w]$, that has the property that, during the

Algorithm 1: Compute all $high(v)$ and $highD(v)$, for all vertices $v \neq r$

```
initialize a DSU structure on the vertices of G, where the link operations are
  predetermined by the edges of T
for v = n to v = 1 do
    foreach u adjacent to v do
        if u is a descendant of v then
            x ← find(u)
            while x > v do
                high[x] ← v
                highD[x] ← u
                next ← find(p(x))
                link(x, p(x))
                x ← next
            end
        end
    end
end
```

course of the algorithm, when we process a vertex v, all back-edges that start from a descendant of w and end in a proper ancestor of v have their higher end in $T(currentM[w])$ (this means, of course, that $currentM[w]$ is a descendant of w). And so, if we want e.g. to compute $M_{low1}(v)$, we may descend immediately to $currentM[c_1]$, where c_1 is the *low1* child of $M(v)$. In Lemma 2.7, we give a formal proof of the correctness and linear complexity of Algorithms 3 and 4.

Algorithm 2: Compute all $M(v)$ and $nextM(v)$, for all vertices $v \neq r$

```
// Compute all M(v) and nextM(v)
for v = n to v = 2 do
    nextM[v] ← ∅
    c ← v, m ← v
    while M(v) = ∅ do
        if l(m) < v then M(v) ← m, break
        c1 ← low1 child of m
        c2 ← low2 child of m
        if low(c2) < v then M(v) ← m, break
        c ← c1, m ← M(c)
    end
    if c ≠ v then nextM(c) ← v
end
```

Lemma 2.6. *Let v and v' be two vertices such that v' is an ancestor of v with $M(v') = M(v)$. Then, $\tilde{M}(v')$ (resp. $M_{low1}(v')$, resp. $M_{low2}(v')$), if it is defined, is a descendant of $\tilde{M}(v)$ (resp. $M_{low1}(v)$, resp. $M_{low2}(v)$).*

Proof. Let v' be an ancestor of v such that $M(v') = M(v)$.

Assume, first, that $\tilde{M}(v')$ is defined. Then, there exists a back-edge $(x, y) \in B(v')$ where x is a proper descendant of $M(v')$. Since $M(v') = M(v)$, x is a proper descendant of $M(v)$. Furthermore,

Algorithm 3: Compute all $\tilde{M}(v)$, for all vertices $v \neq r$

initialize an array *currentM* with n entries

// Compute all $\tilde{M}(v)$

foreach *vertex* v **do** $currentM[v] \leftarrow v$

for $v = n$ *to* $v = 2$ **do**

  $m \leftarrow M(v)$

  $c \leftarrow$ *low1* child of m

  if $low(c) \geq v$ **then** $\tilde{M}(v) \leftarrow \emptyset$, **continue**

  $c' \leftarrow$ *low2* child of m

  if $low(c') < v$ **then** $\tilde{M}(v) \leftarrow m$, **continue**

  $m \leftarrow currentM[c]$

  while $\tilde{M}(v) = \emptyset$ **do**

    if $l(m) < v$ **then** $\tilde{M}(v) \leftarrow m$, **break**

    $c_1 \leftarrow$ *low1* child of m

    $c_2 \leftarrow$ *low2* child of m

    if $low(c_2) < v$ **then** $\tilde{M}(v) \leftarrow m$, **break**

    $m \leftarrow currentM[c_1]$

  end

  $currentM[c] \leftarrow m$

end

since y is a proper ancestor of v', it is also a proper ancestor of v. This shows that $(x, y) \in B(v)$, and $\tilde{M}(v)$ is an ancestor of x. Due to the generality of (x, y), we conclude that $\tilde{M}(v)$ is an ancestor of $\tilde{M}(v')$.

Now assume that $M_{low1}(v')$ is defined. Then, there exists a back-edge $(x, y) \in B(v')$ where x is a descendant of the *low1* child of $M(v')$. Since $M(v') = M(v)$, x is a descendant of the *low1* child of $M(v)$. Furthermore, since y is a proper ancestor of v', it is also a proper ancestor of v. This shows that $(x, y) \in B(v)$, and $M_{low1}(v)$ is an ancestor of x. Due to the generality of (x, y), we conclude that $M_{low1}(v)$ is an ancestor of $M_{low1}(v')$.

Finally, assume that $M_{low2}(v')$ is defined. Then, there exists a back-edge $(x, y) \in B(v')$ where x is a descendant of the *low2* child of $M(v')$. Since $M(v') = M(v)$, x is a descendant of the *low2* child of $M(v)$. Furthermore, since y is a proper ancestor of v', it is also a proper ancestor of v. This shows that $(x, y) \in B(v)$, and $M_{low2}(v)$ is an ancestor of x. Due to the generality of (x, y), we conclude that $M_{low2}(v)$ is an ancestor of $M_{low2}(v')$. □

Lemma 2.7. *Algorithms 3 and 4 compute all* $\tilde{M}(v)$, $M_{low1}(v)$ *and* $M_{low2}(v)$, *for all vertices* $v \neq r$, *in total linear time.*

Proof. Let us show e.g. that Algorithm 4 correctly computes all $M_{low1}(v)$, for all $v \neq r$, in total linear time. The proofs for the other cases are similar. So let v be a vertex $\neq r$. Since we are interested in the back-edges $(x, y) \in B(v)$ with x a descendant of the *low1* child c of $M(v)$, we first have to check whether $low(c) < v$. If $low(c) \geq v$, then there is no such back-edge, and therefore we set $M_{low1}(v) \leftarrow \emptyset$ (in line 6). If $low(c) < v$, then $M_{low1}(v)$ is defined, and in line 7 we assign m the value $currentM[c]$. We claim that, at that moment, $currentM[c]$ is an ancestor of $M_{low1}(v)$, and every $currentM[c_1]$ that we will access in the **while** loop in line 13 is also an ancestor of $M_{low1}(v)$; furthermore, when we reach line 15, $currentM[c]$ is assigned $M_{low1}(v)$. It is not difficult to see this

Algorithm 4: Compute all $M_{low1}(v)$ and $M_{low2}(v)$, for all vertices $v \neq r$

1 initialize an array *currentM* with n entries
// *Compute all* $M_{low1}(v)$
2 **foreach** *vertex* v **do** $currentM[v] \leftarrow v$
3 **for** $v = n$ *to* $v = 2$ **do**
4     $m \leftarrow M(v)$
5     $c \leftarrow$ *low1* child of m
6   **if** $low(c) \geq v$ **then** $M_{low1}(v) \leftarrow \emptyset$, **continue**
7     $m \leftarrow currentM[c]$
8   **while** $M_{low1}(v) = \emptyset$ **do**
9   **if** $l(m) < v$ **then** $M_{low1}(v) \leftarrow m$, **break**
10         $c_1 \leftarrow$ *low1* child of m
11         $c_2 \leftarrow$ *low2* child of m
12   **if** $low(c_2) < v$ **then** $M_{low1}(v) \leftarrow m$, **break**
13         $m \leftarrow currentM[c_1]$
14   **end**
15     $currentM[c] \leftarrow m$
16 **end**
// *Compute all* $M_{low2}(v)$
17 **foreach** *vertex* v **do** $currentM[v] \leftarrow v$
18 **for** $v = n$ *to* $v = 2$ **do**
19     $m \leftarrow M(v)$
20     $c \leftarrow$ *low2* child of m
21   **if** $low(c) \geq v$ **then** $M_{low2}(v) \leftarrow \emptyset$, **continue**
22     $m \leftarrow currentM[c]$
23   **while** $M_{low2}(v) = \emptyset$ **do**
24   **if** $l(m) < v$ **then** $M_{low2}(v) \leftarrow m$, **break**
25         $c_1 \leftarrow$ *low1* child of m
26         $c_2 \leftarrow$ *low2* child of m
27   **if** $low(c_2) < v$ **then** $M_{low2}(v) \leftarrow m$, **break**
28         $m \leftarrow currentM[c_1]$
29   **end**
30     $currentM[c] \leftarrow m$
31 **end**

inductively. Suppose, then, that this was the case for every vertex $v' > v$, and let us see what happens when we process v. Let c be the *low1* child of $M(v)$. Initially, $currentM[c]$ was set to be c. Now, if $currentM[c]$ is still c, $M_{low1}(v)$ is a descendant of c (by definition). Otherwise, due to the inductive hypothesis, $currentM[c]$ had been assigned $M_{low1}(v')$ during the processing of a vertex $v' > v$ with $M(v') = M(v)$. This implies that v' is a descendant of v, and by Lemma 2.6 we have that $M_{low1}(v')$ is an ancestor of $M_{low1}(v)$. In any case, then, we have that $m = currentM[c]$ in an ancestor of $M_{low1}(v)$. Now we enter the **while** loop in line 8. If either $l(m) < v$ or $low(c_2) < v$, where c_2 is the *low2* child of m, we have that $M_{low1}(v)$ is an ancestor of m. Since m is also an ancestor of $M_{low1}(v)$, we correctly set $M_{low1}(v) \leftarrow m$ (in lines 9 or 12). Otherwise, we have that $M_{low1}(v)$ is a descendant of the *low1* child c_1 of m. Now, due to the inductive hypothesis, $currentM[c_1]$ is either c_1 or $M_{low1}(v')$ for a vertex $v' > v$ with $M(v') = m$. In the first case we obviously have that $currentM[c_1]$ is an ancestor of $M_{low1}(v)$. Now assume that the second case is true, and let (x,y) be a back-edge with x a descendant of c_1 and y a proper ancestor of v. Then, since $v' > v$ and v, v' have m as a common descendant, we have that v is ancestor of v', and therefore y is a proper ancestor of v'. This shows that x is a descendant of $M_{low1}(v')$. Thus, due to the generality of (x,y), we have that $M_{low1}(v)$ is a descendant of $M_{low1}(v')$. In any case, then, we have that $currentM[c_1]$ is an ancestor of $M_{low1}(v)$. Thus we set $m \leftarrow currentM[c_1]$ and we continue the **while** loop, until we have that $m = M_{low1}(v)$, in which case we will set $currentM[c] \leftarrow m$ in line 15. Thus we have proved that Algorithm 4 correctly computes $M_{low1}(v)$, for every vertex $v \neq r$, and that, during the processing of a vertex v, every $currentM[c]$ that we access is an ancestor of $M_{low1}(v)$ (until, in line 15, we assign $currentM[c]$ to $M_{low1}(v)$).

Now, to prove linearity, let $S(v) = \{m_1, \dots, m_k\}$, ordered increasingly, denote the (possible empty) set of all vertices that we had to descend to before leaving the **while** loop in lines 8-14. (Thus, if $k \geq 1$, $m_k = M_{low1}(v)$.) In other words, $S(v)$ contains all vertices that were assigned to m in line 13. We will show that Algorithm 4 runs in linear time, by showing that, for every two vertices v and v', $v \neq v'$ implies that $S(v) \cap S(v') \subseteq \{M_{low1}(v)\}$, where we have $S(v) \cap S(v') = \{M_{low1}(v)\}$ only if $M_{low1}(v) = M_{low1}(v')$. Of course, it is definitely the case that $S(v) \cap S(v') = \emptyset$ if v and v' are not related as ancestor and descendant, since the **while** loop descends to descendants of the vertex under processing. So let v' be a proper ancestor of v. If $M_{low1}(v')$ is not a descendant of the *low1* child c of $M(v)$, then we obviously have $S(v) \cap S(v') = \emptyset$ (since $S(v)$ consists of descendants of c, but the **while** loop during the computation of $M_{low1}(v')$ will not descend to the subtree of c). Thus we may assume that $M_{low1}(v')$ is a descendant of c. Now, let $S(v') = \{m_1, \dots, m_k\}$ and $m_0 = currentM[c']$, where c' is the *low1* child of $M(v')$. We will show that every m_i, for every $i \in \{1, \dots, k\}$, is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$. (This obviously implies that $S(v') \cap S(v) \subseteq \{M_{low1}(v)\}$.) First observe that $M(v')$ is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$. To see this, suppose that $M(v')$ is not an ancestor of $M(v)$. Since $M_{low1}(v')$ is a descendant of c, there is at least one back-edge (x,y) in $B(v')$ with x a descendant of c. Then, since y is a proper ancestor of v' and v' is a proper ancestor of v, we have that (x,y) is in $B(v)$, and therefore x is a descendant of $M_{low1}(v)$. Now let (x',y') be a back-edge in $B(v')$. If x' is a descendant of a vertex in $T[c,v']$, but not a descendant of c, then the nearest common ancestor of x and x' is in $T[M(v),v']$, and therefore $M(v')$ is an ancestor of $M(v)$, contradicting our supposition. Thus, x' is a descendant of c. Furthermore, y' is a proper ancestor of v, and therefore $(x',y') \in B(v)$. Thus, x' is a descendant of $M_{low1}(v)$. Due to the generality of $(x',y') \in B(v')$, we conclude that $M(v')$ is a descendant of $M_{low1}(v)$. Thus we have shown that $M(v')$ is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$.

Now, if $M(v')$ is a descendant of $M_{low1}(v)$, we obviously have $S(v) \cap S(v') = \emptyset$. Let's assume, then, that $M(v')$ is an ancestor of $M(v)$. If $M(v')$ coincides with $M(v)$, then $c' = c$, and so m_0 coincides with $currentM[c]$, which is a descendant of $M_{low1}(v)$ (since $M_{low1}(v)$ has already been calculated), and therefore every m_i, for every $i \in \{1, \dots, k\}$, is a proper descendant of $M_{low1}(v)$ (since m_1, if it exists, is a proper descendant of m_0), and so we have $S(v') \cap S(v) = \emptyset$. So let's assume that $M(v')$ is a proper ancestor of $M(v)$. Then, c' is an ancestor of $M(v)$. Suppose that m_0 is not an ancestor of $M(v)$. This means that $currentM[c'] \neq c'$, and therefore there is a vertex $\tilde{v} > v'$ with $M(\tilde{v}) = M(v')$ and $M_{low1}(\tilde{v}) = currentM[c']$. Furthermore, since m_0 is not an ancestor of $M(v)$, it must be a descendant of c. Now, since v' is an ancestor of v and $M(v')$ is a proper ancestor of $M(v)$, Lemma 2.4 implies that $M(v')$ is a proper ancestor of v. Since $M(v') = M(\tilde{v})$, this implies that $M(\tilde{v})$ is a proper ancestor of v, and therefore $\tilde{v}$ is a proper ancestor of v. Now let (x,y) be a back-edge in $B(\tilde{v})$ such that x is a descendant of $M_{low1}(\tilde{v}) = currentM[c'] = m_0$. Then, since m_0 is a descendant of c, x is also descendant of c. Furthermore, since $\tilde{v}$ is an ancestor of v, y is a proper ancestor of v. This shows that x is a descendant of $M_{low1}(v)$. Due to the generality of (x, y), we conclude that $M_{low1}(\tilde{v})$ is a descendant of $M_{low1}(v)$. Thus we have shown that m_0 is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$.

Now let's assume that m_i is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$, for some $i \in \{0, \ldots, k-1\}$. We will prove that the same is true for m_{i+1}. If m_i is a descendant of $M_{low1}(v)$, then the same is true for m_{i+1}. Let's assume, then, that m_i is an ancestor of $M(v)$. Now we have that $m_{i+1} = \mathit{currentM}[c_1]$, where c_1 is the *low1* child of m_i. If $m_i = M(v)$, then we have $c_1 = c$, and therefore $\mathit{currentM}[c_1] = \mathit{currentM}[c]$ is a descendant of $M_{low1}(v)$ (since $M_{low1}(v)$ has already been computed). Suppose, then, that m_i is a proper ancestor of $M(v)$. Then, c_1 is an ancestor of $M(v)$. If $\mathit{currentM}[c_1] = c_1$, we obviously have that $\mathit{currentM}[c_1]$ is an ancestor of $M(v)$. Otherwise, if $\mathit{currentM}[c_1] \neq c_1$, there is a vertex $\tilde{v}$ such that $M(\tilde{v}) = m_i$ and $\mathit{currentM}[c_1] = M_{low1}(\tilde{v})$. Assume, first, that $\tilde{v}$ is an ancestor of v. Suppose that $M_{low1}(\tilde{v})$ is not an ancestor of $M(v)$. Then it must be a descendant of c. Let (x, y) be a back-edge in $B(\tilde{v})$ with x a descendant of $M_{low1}(\tilde{v})$. Then x is a descendant of c. Furthermore, y is a proper ancestor of $\tilde{v}$, and therefore a proper ancestor of v. This shows that x is a descendant of $M_{low1}(v)$. Due to the generality of (x, y), we conclude that $M_{low1}(\tilde{v})$ is a descendant of $M_{low1}(v)$. Thus, if $\tilde{v}$ is an ancestor of v, $M_{low1}(\tilde{v})$ is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$. Suppose, now, that $\tilde{v}$ is a descendant of v. Let (x, y) be a back-edge in $B(v)$. Then, x is a descendant of $M(v)$, and therefore a descendant of c_1. Furthermore, y is a proper ancestor of v, and therefore a proper ancestor of $\tilde{v}$. This shows that x is a descendant of $M_{low1}(\tilde{v})$. Due to the generality of (x, y), we conclude that $M(v)$ is a descendant of $M_{low1}(\tilde{v})$. In any case, then, m_{i+1} is either an ancestor of $M(v)$ or a descendant of $M_{low1}(v)$. Thus, $S(v) \cap S(v') \subseteq \{M_{low1}(v)\}$ is established. □

3 Computing the 3-cuts of a 3-edge-connected graph

In this section we present a linear-time algorithm that computes all the 3-edge-cuts of a 3-edge-connected graph $G = (V, E)$. It is well-known that the number of the 3-edge-cuts of G is $O(n)$ [17] (e.g., it follows from the definition of the cactus graph [1, 13]), but we provide an independent proof of this fact. Then, in Section 4.1, we show how to extend this algorithm so that it can also count the number of minimal 3-edge-cuts of a general graph. Note that there can be $O(n^3)$ such cuts [2].

Our method is to classify the 3-cuts on the DFS-tree T in a way that allows us to compute them efficiently. If $\{e_1, e_2, e_3\}$ is a 3-cut, we can initially distinguish three cases: either e_1 is a tree-edge and both e_2 and e_3 are back-edges (section 3.1), or e_1 and e_2 are two tree-edges and e_3 is a back-edge (section 3.2), or e_1, e_2 and e_3 is a triplet of tree-edges (section 3.3). Then, we divide those cases in subcases based on the concepts we have introduced in the previous section. Figure 1 gives a general overview of the cases we will handle in detail in the following sections.

3.1 One tree-edge and two back-edges

Lemma 3.1. *Let $\{(u, p(u)), e, e'\}$ be a 3-cut such that e and e′ are back-edges. Then $B(u) = \{e, e'\}$. Conversely, if for a vertex $u \neq r$ we have $B(u) = \{e, e'\}$ where e and e' are back-edges, then $\{(u, p(u)), e, e'\}$ is a 3-cut.*

Proof. After removing the tree-edge $(u, p(u))$, the edges that connect $T(u)$ with the rest of the graph are precisely those contained in $B(u)$. Let e and e' be two back-edges in $B(u)$. Then it is obvious that $\{(u, p(u)), e, e'\}$ is a 3-cut if and only if $B(u)$ consists precisely of these two back-edges. □

Thus, to find all 3-cuts of the form $\{(u, p(u)), e, e'\}$, where e and e' are back-edges, we only have to store, for every vertex u, two back-edges $e, e' \in B(u)$. Since $(\mathit{low1D}(u), \mathit{low1}(u))$ and

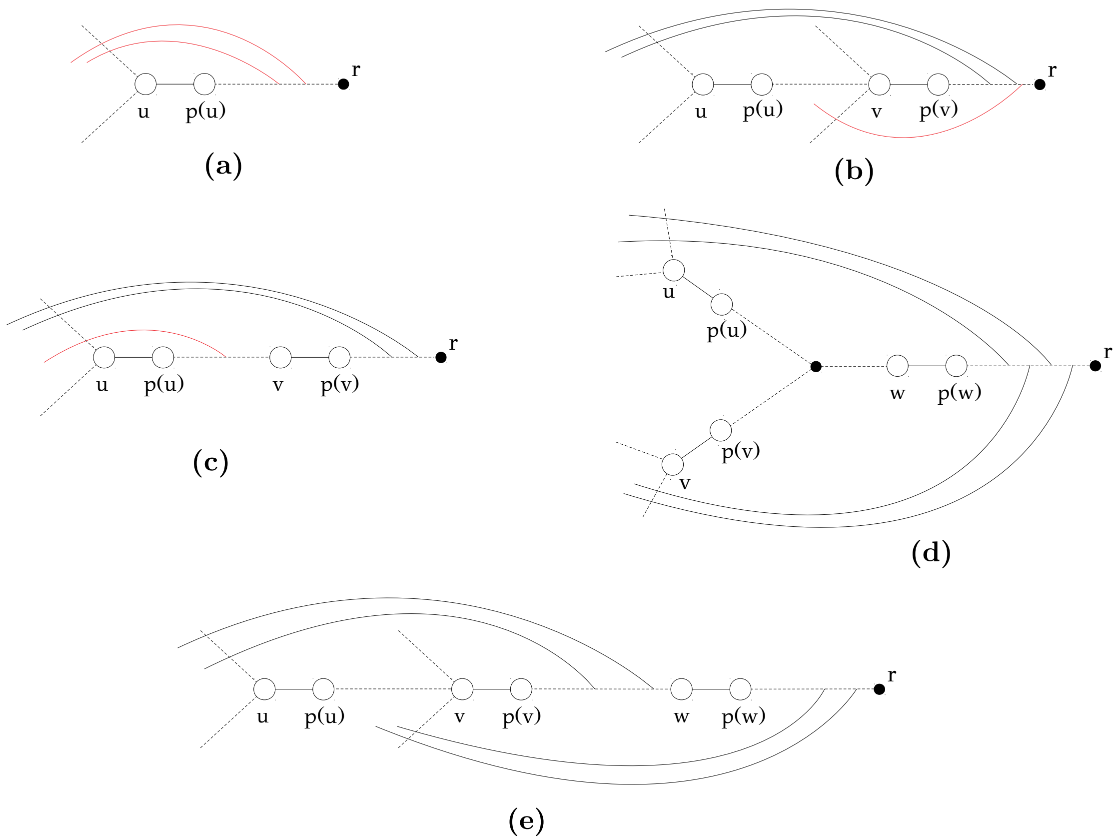

Figure 1: The types of 3-cuts with respect to a DFS-tree. **(a)** One tree-edge $(u, p(u))$ and two back-edges (section 3.1). **(b)** Two tree-edges $(u, p(u))$ and $(v, p(v))$, where u is a descendant of v, and one-back edge in $B(v) \setminus B(u)$ (section 3.2.1). **(c)** Two tree-edges $(u, p(u))$ and $(v, p(v))$, where u is a descendant of v, and one-back edge in $B(u) \setminus B(v)$ (section 3.2.2). **(d)** Three tree-edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, where w is an ancestor of u and v, but u and v are not related as ancestor and descendant (section 3.3.1). **(d)** Three tree-edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, where u is a descendant of v and v is a descendant of w (section 3.3.2).

$(low2D(u), low2(u))$ are two such back-edges, we mark the triplet $\{(u, p(u)), (low1D(u), low1(u)), (low2D(u), low2(u))\}$, for every u that has $b\_count(u) = 2$.

3.2 Two tree-edges and one back-edge

Lemma 3.2. *Let $\{(u, p(u)), (v, p(v)), e\}$ be a 3-cut such that e is a back-edge. Then u and v are related as ancestor and descendant.*

Proof. Suppose that u and v are not related as ancestor or descendant. Since the graph is 3-edge-connected, $b\_count(u) > 1$, and therefore there is least one back-edge $(x, y) \in B(u) \setminus \{e\}$. Since v is not a descendant of u, $v \notin T[x, u]$; and since v is not an ancestor of u, $v \notin T[p(u), y]$. Thus, by removing the edges $(u, p(u))$, $(v, p(v))$, and e, from the graph, u remains connected with $p(u)$, through the path $T[u, x], (x, y), T[p(u), y]$. This contradicts that fact that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut. □

Proposition 3.3. *Let $\{(u, p(u)), (v, p(v)), e\}$ be a 3-cut, where e is a back-edge. Then, either (1) $B(v) = B(u) \sqcup \{e\}$ or (2) $B(u) = B(v) \sqcup \{e\}$. Conversely, if there exists a back-edge e such that (1) or (2) is true, then $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut.*

Proof. ($\Rightarrow$) By Lemma 3.2, we may assume, without loss of generality, that v is an ancestor of u. Now, suppose that (1) does not hold; we will prove that (2) does. Since (1) is not true, there must exist a back-edge e' such that $e' \in B(v)$ and $e' \notin B(u) \cup \{e\}$, or $e' \notin B(v)$ and $e' \in B(u) \cup \{e\}$. Suppose the first is true: that is, there exists a back-edge (x, y) such that $(x, y) \in B(v)$ and $(x, y) \notin B(u) \cup \{e\}$. Then y is an ancestor of v, and therefore an ancestor of u. But, since $(x, y) \notin B(u)$, x cannot be a descendant of u, and thus it belongs to $T(v) \setminus T(u)$. Now, by removing the edges $(u, p(u))$, $(v, p(v))$ and e from the graph, we can see that v remains connected with $p(v)$ through the path $T[v, x], (x, y), T[y, p(v)]$. This contradicts the fact that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut. Thus we have shown that there exists a back-edge e' such that $e' \notin B(v)$ and $e' \in B(u) \cup \{e\}$, and also that $B(v) \subseteq B(u) \cup \{e\}$. Now, suppose that there exists a back-edge $(x, y) \neq e$ such that $(x, y) \notin B(v)$ and $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of v. But, since $(x, y) \notin B(v)$, y is not a proper ancestor of v, and thus belongs to $T[p(u), v]$. Now, by removing the edges $(u, p(u))$, $(v, p(v))$ and e from the graph, we can see that u remains connected with $p(u)$ through the path $T[u, x], (x, y), T[y, p(u)]$. This contradicts the fact that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut. Thus we have shown that e is the unique back-edge such that $e \notin B(v)$ and $e \in B(u)$, and also that $B(u) \subseteq B(v) \cup \{e\}$. In conjunction with $B(v) \subseteq B(u) \cup \{e\}$, this implies that $B(u) = B(v) \sqcup \{e\}$.

($\Leftarrow$) First, observe that both (1) and (2) imply that u and v are related as ancestor and descendant: Since the graph is 2-edge-connected, we have $b\_count(x) > 0$, for every vertex $x \neq r$; and whenever we have $B(u) \cap B(v) \neq \emptyset$, for two vertices u and v, (and such is the case if either (1) or (2) is true), we can infer that u and v are related as ancestor and descendant. Now, due to the symmetry of the relations (1) and (2), we may assume, without loss of generality, that v is an ancestor of u. Let's assume first that (1) is true, and let $e = (x, y)$. Since $(x, y) \in B(v)$, y is a proper ancestor of v, and therefore a proper ancestor of u. But, since $(x, y) \notin B(u)$, x cannot be a descendant of u, and thus it belongs to $T(v) \setminus T(u)$. Furthermore, this is the only back-edge that starts from $T(v) \setminus T(u)$ and ends in a proper ancestor of v, since $B(v) \setminus \{e\} = B(u)$. Thus we can see that, by removing the edges $(u, p(u))$, $(v, p(v))$ and e from the graph, the graph becomes disconnected. (For the subgraph $T(v) \setminus T(u)$ becomes disconnected from $T(u) \cup (T(r) \setminus T(v))$.) Now assume that (2) is true, and let $e = (x, y)$. Since $(x, y) \in B(u)$, x is a descendant of u, and therefore a descendant of v. But, since $(x, y) \notin B(v)$, y is not a proper ancestor of v, and thus it belongs to $T[p(u), v]$. Furthermore, it is the only back-edge that starts from $T(u)$ and ends in $T[p(u), v]$, since $B(u) \setminus \{e\} = B(v)$. Thus we can see that, by removing the edges $(u, p(u))$, $(v, p(v))$ and e from the graph, the graph becomes disconnected. (For the subgraph $T(v) \setminus T(u)$ becomes disconnected from $T(u) \cup (T(r) \setminus T(v))$.) □

Here we distinguish two cases, depending on whether $B(v) = B(u) \sqcup \{e\}$ or $B(u) = B(v) \sqcup \{e\}$.

3.2.1 v is an ancestor of u and $B(v) = B(u) \sqcup \{e\}$.

Throughout this section let $V(u)$ denote the set of vertices v that are ancestors of u and such that $B(v) = B(u) \sqcup \{e\}$, for a back-edge e. By proposition 3.3, this means that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut. The following lemma shows that, for every vertex v, there is at most one vertex u such that $v \in V(u)$.

Lemma 3.4. *Let u, u' be two distinct vertices. Then $V(u) \cap V(u') = \emptyset$.*

Proof. Suppose that there exists a $v \in V(u) \cap V(u')$. Then there are back-edges e, e' such that $B(v) = B(u) \sqcup \{e\}$ and $B(v) = B(u') \sqcup \{e'\}$, and so we have $B(u) \sqcup \{e\} = B(u') \sqcup \{e'\}$. Since $b\_count(u) > 1$ and $b\_count(u') > 1$ (for the graph is 3-edge-connected), we infer that $B(u) \cap B(u') \neq \emptyset$, and thus u and u' are related as ancestor and descendant. Thus we can assume, without loss of generality, that u' is an ancestor of u. Now let $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of u'. Furthermore, since $B(v) = B(u) \sqcup \{e\}$, we have $(x, y) \in B(v)$, and so y is a proper ancestor of v, and therefore a proper ancestor of u'. This shows that $(x, y) \in B(u')$, and thus we have $B(u) \subseteq B(u')$. In conjunction with $B(u) \sqcup \{e\} = B(u') \sqcup \{e'\}$ (which implies that $|B(u)| = |B(u')|$), we infer that $B(u) = B(u')$ (and $e = e'$). This contradicts the fact that the graph is 3-edge-connected. □

Thus, the total number of 3-cuts of the form $\{(u, p(u)), (v, p(v)), e\}$, where u is a descendant of v and e is a back-edge such that $B(v) = B(u) \sqcup \{e\}$, is $O(n)$. Now we will show how to compute, for every vertex v, the vertex u such that $v \in V(u)$ (if such a vertex u exists), together with the back-edge e such that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut, in total linear time.

Let u, v, e be such that $v \in V(u)$ and $B(v) = B(u) \sqcup \{e\}$, and let $e = (x, y)$. Then y is a proper ancestor of v, and therefore a proper ancestor of u, so x cannot be a descendant of v (since $e \notin B(u)$). Thus, x is either on the tree-path $T(u, v]$, or it is a proper descendant of a vertex in $T(u, v]$, but not a descendant of u. In the first case we have $\tilde{M}(v) = M(u)$ (and $x = M(v)$); in the second case either $M_{low1}(v) = M(u)$ (and $x = M_{low2}(v)$) or $M_{low2}(v) = M(u)$ (and $x = M_{low1}(v)$). (For an illustration, see figure 2.) The following lemma shows how we can determine u from v.

Lemma 3.5. *Let v be an ancestor of u such that $\tilde{M}(v) = M(u)$ or $M_{low1}(v) = M(u)$ or $M_{low2}(v) = M(u)$, and let $m = \tilde{M}(v)$ or $M_{low1}(v)$ or $M_{low2}(v)$, depending on whether $\tilde{M}(v) = M(u)$ or $M_{low1}(v) = M(u)$ or $M_{low2}(v) = M(u)$. Then, $v \in V(u)$ if and only if u is the lowest element in $M^{-1}(m)$ which is greater than v and such that $high(u) < v$ and $b\_count(v) = b\_count(u) + 1$.*

Proof. ($\Rightarrow$) $v \in V(u)$ means that there exists a back-edge e such that $B(v) = B(u) \sqcup \{e\}$. Thus we get immediately $b\_count(v) = b\_count(u) + 1$ as a consequence. Furthermore, since $B(u) \subset B(v)$, we also get $high(u) < v$ (since for every $(x, y) \in B(u)$ it must be the case that y is a proper ancestor of v, and therefore $high(u)$ is a proper ancestor of v). Now, suppose that there exists a $u' \in M^{-1}(m)$ which is lower than u and greater than v. Then, since $B(u) = B(u')$ (and, in particular, $B(u') \subset B(u)$), there is a back-edge $(x, y) \in B(u)$ with $x \in T(u)$ and $y \in T[p(u), u']$. But this contradicts the fact that $high(u) < v$.
($\Leftarrow$) Let $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of v. Furthermore,

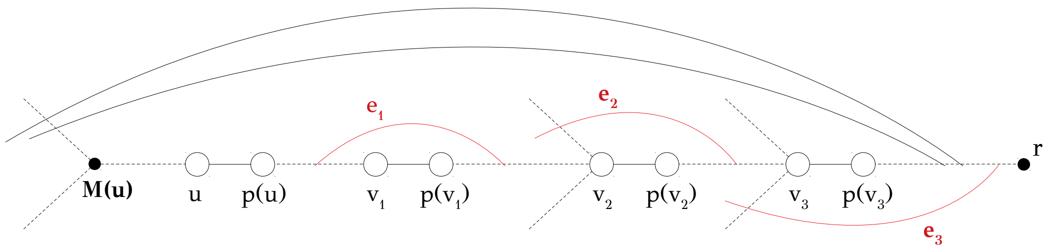

Figure 2: In this example we have $V(u) = \{v_1, v_2, v_3\}$, and every back-edge e_i satisfies $B(v_i) = B(u) \sqcup \{e_i\}$. It should be clear that every $M(v_i)$ is an ancestor of $M(u)$, and $\tilde{M}(v_1) = M(u)$, $M_{low1}(v_2) = M(u)$ and $M_{low2}(v_3) = M(u)$. It is perhaps worth noting that, for every vertex u, we may have many vertices $v \in V(u)$ with $\tilde{M}(v) = M(u)$ or $M_{low1}(v) = M(u)$, but only the lowest v in $V(u)$ may have $M_{low2}(v) = M(u)$.

$high(u) < v$ implies that y is a proper ancestor of v. This shows that $(x, y) \in B(v)$, and thus we have $B(u) \subseteq B(v)$. Then, $b\_count(v) = b\_count(u) + 1$ implies the existence of a back-edge $e \in B(v) \setminus B(u)$ such that $B(v) = B(u) \sqcup \{e\}$. ◻

Thus, for every vertex v, we have to check whether the lowest element u of $M^{-1}(m)$ which is greater than v satisfies $b\_count(v) = b\_count(u) + 1$, for all $m \in \{\tilde{M}(v), M_{low1}(v), M_{low2}(v)\}$. To do this efficiently, we process the vertices in a bottom-up fashion, and we keep in a variable $currentVertex[m]$ the lowest element of $M^{-1}(m)$ currently under consideration, so that we do not have to traverse the list $M^{-1}(m)$ from the beginning each time we process a vertex. Algorithm 5 is an implementation of this procedure.

3.2.2 v is an ancestor of u and $B(u) = B(v) \sqcup \{e\}$.

Throughout this section let $U(v)$ denote the set of vertices u that are descendants of v and such that $B(u) = B(v) \sqcup \{e\}$, for a back-edge e. By proposition 3.3, this means that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut. The following lemma shows that, for every vertex u, there is at most one vertex v such that $u \in U(v)$.

Lemma 3.6. *Let v, v' be two distinct vertices. Then $U(v) \cap U(v') = \emptyset$.*

Proof. Suppose that there exists a $u \in U(v) \cap U(v')$. Then v and v' are related as ancestor and descendant, since they have a common descendant. Thus we may assume, without loss of generality, that v' is an ancestor of v. Let (x, y) be a back-edge in $B(v')$. Then, y is a proper ancestor of v', and therefore a proper ancestor of v. Furthermore, $u \in U(v')$ implies that $B(v') \subseteq B(u)$, and therefore $(x, y) \in B(u)$. Thus, x is a descendant of u, and therefore a descendant of v. This shows that $(x, y) \in B(v)$, and thus we have $B(v') \subseteq B(v)$. Now, $u \in U(v) \cap U(v')$ means that there exist two back-edges e, e' such that $B(u) = B(v) \sqcup \{e\}$ and $B(u) = B(v) \sqcup \{e\}$, and thus we have $B(v) \sqcup \{e\} = B(v') \sqcup \{e'\}$. Therefore, $|B(v)| = |B(v')|$. In conjunction with $B(v') \subseteq B(v)$,

Algorithm 5: Find all 3-cuts $\{(u, p(u)), (v, p(v)), e)\}$, where u is a descendant of v and $B(v) = B(u) \sqcup \{e\}$, for a back-edge e.

initialize an array *currentVertex* with n entries
// $m = \tilde{M}(v)$
foreach *vertex* x **do** $currentVertex[x] \leftarrow x$
for $v \leftarrow n$ *to* $v = 1$ **do**
    $m \leftarrow \tilde{M}(v)$
    if $m = \emptyset$ **then continue**
    // *find the lowest* $u \in M^{-1}(m)$ *which is greater than* v
    $u \leftarrow currentVertex[m]$
    while $nextM(u) \neq \emptyset$ ***and*** $nextM(u) > v$ **do** $u \leftarrow nextM(u)$
    $currentVertex[m] \leftarrow u$
    // *check the condition in lemma 3.5*
    if $high(u) < v$ ***and*** $b\_count(v) = b\_count(u) + 1$ **then**
        mark the triplet $\{(u, p(u)), (v, p(v)), (M(v), l(M(v)))\}$
    end
end
// $m = M_{low1}(v)$
foreach *vertex* x **do** $currentVertex[x] \leftarrow x$
for $v \leftarrow n$ *to* $v = 1$ **do**
    $m \leftarrow M_{low1}(v)$
    if $m = \emptyset$ **then continue**
    // *find the lowest* $u \in M^{-1}(m)$ *which is greater than* v
    $u \leftarrow currentVertex[m]$
    while $nextM(u) \neq \emptyset$ ***and*** $nextM(u) > v$ **do** $u \leftarrow nextM(u)$
    $currentVertex[m] \leftarrow u$
    // *check the condition in lemma 3.5*
    if $high(u) < v$ ***and*** $b\_count(v) = b\_count(u) + 1$ **then**
        mark the triplet $\{(u, p(u)), (v, p(v)), (M_{low2}(v), l(M_{low2}(v)))\}$
    end
end
// $m = M_{low2}(v)$
foreach *vertex* x **do** $currentVertex[x] \leftarrow x$
for $v \leftarrow n$ *to* $v = 1$ **do**
    $m \leftarrow M_{low2}(v)$
    if $m = \emptyset$ **then continue**
    // *find the lowest* $u \in M^{-1}(m)$ *which is greater than* v
    $u \leftarrow currentVertex[m]$
    while $nextM(u) \neq \emptyset$ ***and*** $nextM(u) > v$ **do** $u \leftarrow nextM(u)$
    $currentVertex[m] \leftarrow u$
    $currentVertex[m] \leftarrow prev$
    // *check the condition in lemma 3.5*
    if $high(u) < v$ ***and*** $b\_count(v) = b\_count(u) + 1$ **then**
        mark the triplet $\{(u, p(u)), (v, p(v)), (M_{low1}(v), l(M_{low1}(v)))\}$
    end
end

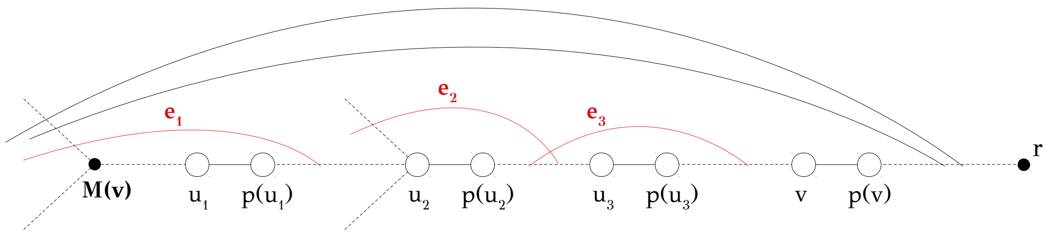

Figure 3: In this example we have $U(v) = \{u_1, u_2, u_3\}$, and every back-edge e_i satisfies $B(u_i) = B(v) \sqcup \{e_i\}$. It should be clear that every $M(u_i)$ is an ancestor of $M(v)$, and $M(u_1) = M(v)$, $M_{low1}(u_2) = M(v)$ and $\tilde{M}(u_3) = M(v)$. It is perhaps worth noting that, for every vertex v, only one $u \in U(v)$ may have $M(u) = M(v)$ (that is, the one satisfying $nextM(u) = v$), but we may have many vertices $u \in V(v)$ with $\tilde{M}(u) = M(v)$ or $M_{low1}(u) = M(v)$.

this implies that $B(v) = B(v')$ (and $e = e'$), contradicting the fact that the graph is 3-edge-connected. ☐

Thus, the total number of 3-cuts of the form $\{(u, p(u)), (v, p(v)), e\}$, where u is a descendant of v and e is a back-edge such that $B(u) = B(v) \sqcup \{e\}$, is $O(n)$. We will now show how to compute, for every vertex u, the vertex v such that $u \in U(v)$ (if such a vertex v exists), together with the back-edge e such that $\{(u, p(u)), (v, p(v)), e\}$ is a 3-cut, in total linear time.

Let u, v, e be such that $u \in U(v)$ and $B(u) = B(v) \sqcup \{e\}$, and let $e = (x, y)$. Then, x is a descendant of u, and therefore a descendant of v. But since $e \notin B(v)$, y is not an ancestor of v, and therefore $y \in T[p(u), v]$. Thus, $y = high(u)$ (and $x = highD(u)$), since every other back-edge $(x', y') \in B(u)$ is also in $B(v)$ and thus has $y' < v \leq y$. This shows how we can determine the back-edge e from a pair of vertices u, v that satisfy $u \in U(v)$. Furthermore, $B(u) = B(v) \sqcup \{e\}$ implies that $M(u)$ is an ancestor of $M(v)$. Thus, either $M(u) = M(v)$, or $M(u)$ is a proper ancestor of $M(v)$. In the second case, we have that either $\tilde{M}(u) = M(v)$ or $M_{low1}(u) = M(v)$ (since the *low* point of u is given by a back-edge in $B(v)$). (For an illustration, see figure 3.) Now the following lemma shows how we can determine v from u.

Lemma 3.7. *Let u be a descendant of v such that $M(u) = M(v)$ or $\tilde{M}(u) = M(v)$ or $M_{low1}(u) = M(v)$, and let $m = M(u)$ or $\tilde{M}(u)$ or $M_{low1}(u)$, depending on whether $M(u) = M(v)$ or $\tilde{M}(u) = M(v)$ or $M_{low1}(u) = M(v)$. Then $u \in U(v)$ if and only if v is the greatest element in $M^{-1}(m)$ which is lower than u and such that $b\_count(u) = b\_count(v) + 1$.*

Proof. ($\Rightarrow$) $u \in U(v)$ means that there exists a back-edge e such that $B(u) = B(v) \sqcup \{e\}$. Thus we get immediately that $b\_count(u) = b\_count(v) + 1$. Now suppose, for the sake of contradiction, that there exists a $v' \in M^{-1}(m)$ which is greater than v and lower than u. Let $(x, y) \in B(v')$. Then y is a proper ancestor of v', and therefore a proper ancestor of u. Furthermore, x is a descendant of $M(v')$ ($= M(v)$), and so every one of the relations $M(u) = M(v)$, $\tilde{M}(u) = M(v)$

or $M_{low1}(u) = M(v)$ implies that x is a descendant of u. This shows that $(x,y) \in B(u)$, and thus we have $B(v') \subseteq B(u)$. Now, since $M(v) = M(v')$ and v' is a proper ancestor of v, we have $B(v) \subset B(v')$. Since $b\_count(u) = b\_count(v)+1$, $B(v) \subset B(v') \subseteq B(u)$ implies that $B(u) = B(v')$, contradicting the fact that the graph is 3-edge-connected.
($\Leftarrow$) Let $(x,y) \in B(v)$. Then y is a proper ancestor of v, and therefore a proper ancestor of u. Furthermore, x is a descendant of $M(v)$, and every one of the relations $M(u) = M(v)$, $\tilde{M}(u) = M(v)$ or $M_{low1}(u) = M(v)$ implies that x is a descendant of $M(u)$. This shows that $(x,y) \in B(u)$. Thus we have $B(v) \subseteq B(u)$, and so $b\_count(u) = b\_count(v) + 1$ implies that there exists a back-edge e such $B(u) = B(v) \sqcup \{e\}$. □

Thus, for every vertex u, we have to check whether the greatest element v in $M^{-1}(m)$ which is lower than u satisfies $b\_count(u) = b\_count(v) + 1$, for all $m \in \{M(u), \tilde{M}(u), M_{low1}(u)\}$. To do this efficiently, we process the vertices in a bottom-up fashion, and we keep in a variable $currentVertex[m]$ the lowest element of $M^{-1}(m)$ currently under consideration, so that we do not have to traverse the list $M^{-1}(m)$ from the beginning each time we process a vertex. Algorithm 6 is an implementation of this procedure.

3.3 Three tree-edges

Lemma 3.8. *Let $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ be a 3-cut, and assume, without loss of generality, that $w < min\{v,u\}$. Then w is an ancestor of both u and v.*

Proof. Suppose that w is neither an ancestor of u nor an ancestor of v. Let $(x,y) \in B(w)$. Then x is a descendant of w, and therefore it is not a descendant of either u or v. In other words, $u,v \notin T[x,w]$. Furthermore, y is a proper ancestor of w. Since neither u nor v is an ancestor of w (since $w < min\{v,u\}$), we have that $u,v \notin T[w,r]$, and therefore $u,v \notin T[w,y]$. Thus, by removing the tree-edges $(u,p(u))$, $(v,p(v))$ and $(w,p(w))$, w remains connected with $p(w)$ through the path $T[w,x],(x,y),T[y,p(w)]$, contradicting the fact that $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ is a 3-cut. This shows that w is an ancestor of either u or v (or both). Suppose, for the sake of contradiction, that w is not an ancestor of u. Then w is an ancestor of v. This implies that u is not a descendant of v (for otherwise it would be a descendant of w). If u is an ancestor of v, it must necessarily be an ancestor of w (because $v \in T(w)$ and $u \notin T(w)$), but $w < u$ forbids this case. Thus, u is not a ancestor of v. So far, then, we have that u is not related as ancestor and descendant with either w or v. Thus we may follow the same reasoning as above, to conclude that, by removing the tree-edges $(u,p(u))$, $(v,p(v))$ and $(w,p(w))$, u remains connected with $p(u)$, again contradicting the fact that $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ is a 3-cut. This shows that w is an ancestor of u. Using the same argument we can also prove that w is an ancestor of v. □

At this point we distinguish two cases, depending on whether u and v are related as ancestor and descendant.

3.3.1 u and v are not related as ancestor and descendant

In what follows we will provide some characterizations of the 3-cuts of the form $\{(u,p(u)),(v,p(v)),(w,p(w))\}$, where w is an ancestor of u and v, and u,v are not related as ancestor and descendant. It will be useful to keep in mind the situation depicted in Figure 4.

Proposition 3.9. *Let u and v be two vertices which are not related as ancestor and descendant, and let w be an ancestor of both u and v. Then, $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ is a 3-cut if and only if $B(w) = B(u) \sqcup B(v)$.*

Algorithm 6: Find all 3-cuts $\{(u,p(u)),(v,p(v)),e\}$, where u is a descendant of v and $B(u) = B(v) \sqcup \{e\}$, for a back-edge e.

initialize an array *currentVertex* with n entries
// $m = M(v)$; *just check whether the condition of Lemma 3.7 is satisfied for* $nextM(u)$
if $b\_count(u) = b\_count(nextM(u)) + 1$ **then**
  mark the triplet $\{(u,p(u)),(nextM(u),p(nextM(u))),(highD(u),high(u))\}$
end
// $m = \tilde{M}(u)$
foreach *vertex* x **do** $currentVertex[x] \leftarrow x$
for $u \leftarrow n$ *to* $u = 1$ **do**
  $m \leftarrow \tilde{M}(u)$
  if $m = \emptyset$ **then continue**
  // *find the greatest* $v \in M^{-1}(m)$ *which is lower than* u
  $v \leftarrow currentVertex[m]$
  while $v \neq \emptyset$ ***and*** $v \geq u$ **do** $v \leftarrow nextM(v)$
  $currentVertex[m] \leftarrow v$
  // *check the condition in Lemma 3.7*
  if $b\_count(u) = b\_count(v) + 1$ **then**
    mark the triplet $\{(u,p(u)),(v,p(v)),(highD(u),high(u))\}$
  end
end
// $m = M_{low1}(u)$
foreach *vertex* x **do** $currentVertex[x] \leftarrow x$
for $u \leftarrow n$ *to* $u = 1$ **do**
  $m \leftarrow M_{low1}(u)$
  if $m = \emptyset$ **then continue**
  // *find the greatest* $v \in M^{-1}(m)$ *which is lower than* u
  $v \leftarrow currentVertex[m]$
  while $v \neq \emptyset$ ***and*** $v \geq u$ **do** $v \leftarrow nextM(v)$
  $currentVertex[m] \leftarrow v$
  // *check the condition in Lemma 3.7*
  if $b\_count(u) = b\_count(v) + 1$ **then**
    mark the triplet $\{(u,p(u)),(v,p(v)),(highD(u),high(u))\}$
  end
end

Proof. (⇒) Let $(x, y) \in B(w)$, and let's assume that $(x, y) \notin B(u)$. Since y is a proper ancestor of w, and therefore a proper ancestor of u, from $(x, y) \notin B(u)$ we infer that x is not a descendant of u. Suppose for the sake of contradiction that x is not a descendant of v, either. This means that neither u nor v is in $T[x, w]$, and so, by removing the edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, w remains connected with $p(w)$ through the path $T[w, x], (x, y), T[y, p(w)]$. This contradicts that fact that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Thus we have established that x is a descendant of v. Since y is also a proper ancestor of v, we have $(x, y) \in B(v)$. Thus we have shown that $B(w) \subseteq B(u) \cup B(v)$. Conversely, let $(x, y) \in B(u) \cup B(v)$, and assume, without loss of generality, that $(x, y) \in B(u)$. Then, x is a descendant of u, and therefore a descendant of w. Now suppose, for the sake of contradiction, that y is not a proper ancestor of w. Then we have $w \notin T[p(u), y)$, and since w is not a descendant of u, we also have $w \notin T[x, u]$. Furthermore, since u and v are not related as ancestor and descendant, v is not contained neither in $T[p(u), y)$ nor in $T[x, u]$. Thus, by removing the edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, u remains connected with $p(u)$ through the path $T[u, x], (x, y), T[y, p(u)]$. This contradicts that fact that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Thus we have shown that y is a proper ancestor of w, and so we have that $(x, y) \in B(w)$. Thus we have established that $B(u) \cup B(v) \subseteq B(w)$, and so we have $B(w) = B(u) \cup B(v)$. Since u and v are not related as ancestor and descendant, we have $B(u) \cap B(v) = \emptyset$. We conclude that $B(w) = B(u) \sqcup B(v)$.

(⇐) Consider the sets of vertices $T(u)$, $T(v)$, $A = T(w) \setminus (T(u) \cup T(v))$ and $B = T(r) \setminus T(w)$. Since u and v are not related as ancestor and descendant, and w is an ancestor of both u and v, these sets are mutually disjoint. Now, since $B(u) \subset B(w)$, all back-edges that start from $T(u)$ end either in $T(u)$ or in B. Similarly, since $B(v) \subset B(w)$, all back-edges that start from $T(v)$ end either in $T(v)$ or in B. Furthermore, a back-edge that starts from A cannot reach B and must necessarily end in A, since it starts from a descendant of w, but not from a descendant of either u or v (while we have $B(w) = B(u) \sqcup B(v)$). Thus, by removing from the graph the tree-edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, the graph becomes separated into two parts: $T(u) \cup T(v) \cup B$ and A. □

Lemma 3.10. *Let u and v be two vertices which are not related as ancestor and descendant, and let w be an ancestor of both u and v. Then $B(w) = B(u) \sqcup B(v)$ if and only if: $M_{low1}(w) = M(u)$ and $M_{low2}(w) = M(v)$ (or $M_{low1}(w) = M(v)$ and $M_{low2}(w) = M(u)$), and $high(u) < w$, $high(v) < w$, and $b\_count(w) = b\_count(u) + b\_count(v)$.*

Proof. (⇒) $b\_count(w) = b\_count(u) + b\_count(v)$ is an immediate consequence of $B(w) = B(u) \sqcup B(v)$. Furthermore, since every $(x, y) \in B(u)$ is also in $B(w)$, it has $y < w$, and so $high(u) < w$. With the same reasoning, we also get $high(v) < w$. Now, since $B(w) = B(u) \sqcup B(v)$, we have that $M(w)$ is an ancestor of both $M(u)$ and $M(v)$. Since u and v are not related as ancestor and descendant, $M(u)$ and $M(v)$ are not related as ancestor or descendant, either. This implies that they are both proper descendants of $M(w)$. Now, suppose, for the sake of contradiction, that $M(u)$ and $M(v)$ are descendants of the same child c of $M(w)$. Then there must exist a back-edge $(x, y) \in B(w)$ such that $x = M(w)$ or x is a descendant of a child of $M(w)$ different from c. (Otherwise, $M(w)$ would be a descendant of c, which is absurd.) But this contradicts the fact that $B(w) = B(u) \sqcup B(v)$, since (x, y) does not belong neither in $B(u)$ nor in $B(v)$. Thus, $M(u)$ and $M(v)$ are descendants of different children of $M(w)$. Furthermore, since every back-edge $(x, y) \in B(w)$ has x in $T(u)$ or $T(v)$, there are no other children of $M(w)$ from whose subtrees begin back-edges that end in a proper ancestor of w. Thus, one of $M(u)$ and $M(v)$ is a descendant of the *low1* child of $M(w)$, and the other is a descendant of the *low2* child of $M(w)$. We may assume, without loss of generality, that $M(u)$ is a descendant of the *low1* child of $M(w)$, and $M(v)$ is a descendant of the *low2* child of $M(w)$. Since $B(u) \subset B(w)$, we have that $M(u)$ is a descendant of

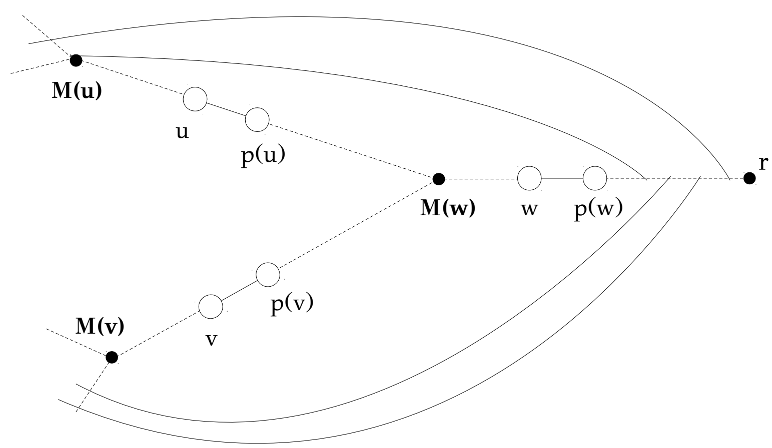

Figure 4: In this example we have $B(w) = B(u) \sqcup B(v)$. Observe that $M_{low1}(w) = M(u)$ and $M_{low2}(w) = M(v)$. Furthermore, $high(u) < w$ and $high(v) < w$. Also, if there is another vertex u' with $M(u') = M(u)$, it must either be a descendant of u or an ancestor of w. Thus, u is the lowest vertex in $M^{-1}(M_{low1}(w))$ which is greater than w. Similarly, v is the lowest vertex in $M^{-1}(M_{low2}(w))$ which is greater than w. By Lemmata 3.10 and 3.11, these properties (together with $b\_count(w) = b\_count(u) + b\_count(v)$) are sufficient to establish $B(w) = B(u) \sqcup B(v)$. Notice also that, if we remove the tree-edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, the graph becomes disconnected into two components: $T(u) \cup T(v) \cup (T(r) \setminus T(w))$ and $T(w) \setminus (T(u) \cup T(v))$. (See also the "$\Leftarrow$" part of the proof of proposition 3.9.)

$M_{low1}(w)$. Furthermore, since $B(w) = B(u) \sqcup B(v)$ and $M(v)$ is not a descendant of the *low1* child of $M(w)$, there are no back-edges (x, y) with x a descendant of the *low1* child of $M(w)$ and y a proper ancestor of w apart from those contained in $B(u)$. Thus, $M(u)$ is an ancestor of $M_{low1}(w)$, and $M_{low1}(w) = M(u)$ is established. With the same reasoning, we also get $M_{low2}(w) = M(v)$.
($\Leftarrow$) Let $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of w. Furthermore, since $high(u) < w$, we have $y < w$, and therefore y is a proper ancestor of w. This shows that $(x, y) \in B(w)$, and thus $B(u) \subseteq B(w)$. With the same reasoning, we also get $B(v) \subseteq B(w)$. Thus we have $B(u) \cup B(v) \subseteq B(w)$. Since u and v are not related as ancestor and descendant, we have $B(u) \cap B(v) = \emptyset$. From $B(u) \cup B(v) \subseteq B(w)$, $B(u) \cap B(v) = \emptyset$, and $b\_count(w) = b\_count(u) + b\_count(v)$, we conclude that $B(w) = B(u) \sqcup B(v)$. □

The following lemma shows, that, for every vertex w, there is at most one pair u, v of descendants of w which are not related as ancestor and descendant and are such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Thus, the number of 3-cuts of this type is $O(n)$. Furthermore, it allows us to compute u and v (if such a pair of u and v exists).

Lemma 3.11. *Let $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ be a 3-cut such that u and v are not related as ancestor and descendant and let w is an ancestor of both u and v. Assume w.l.o.g. that $M_{low1}(w) = M(u)$ and $M_{low2}(w) = M(v)$, and let $m_1 = M_{low1}(w)$ and $m_2 = M_{low2}(w)$. Then u is the lowest vertex in $M^{-1}(m_1)$ which is greater than w, and v is the lowest vertex in $M^{-1}(m_2)$ which is greater that w.*

Proof. By Proposition 3.9, we have that $B(w) = B(u) \sqcup B(v)$. Now, suppose that there exists a $u' \in M^{-1}(m_1)$ which is lower than u and greater than w. Then, $M(u') = M(u)$ implies that $B(u') \subset B(u)$, and so there is a back-edge $(x, y) \in B(u) \setminus B(u')$. This means that y is not a proper ancestor of u', and therefore not a proper ancestor of w, either. But this implies that $(x, y) \notin B(w)$, contradicting the fact that $B(u) \subset B(w)$. A similar argument shows that there does not exist a $v' \in M^{-1}(m_2)$ which is lower than v and greater than w. □

Thus we only have to find, for every vertex w, the lowest element u of $M^{-1}(M_{low1}(w))$ which is greater than w, and the lowest element v of $M^{-1}(M_{low2}(w))$ which is greater than w, and check the condition in Lemma 3.10 - i.e., whether $high(u) < w$, $high(v) < w$, and $b\_count(w) = b\_count(u) + b\_count(v)$. To do this efficiently, we process the vertices in a bottom-up fashion, and we keep in a variable *currentVertex*$[x]$ the lowest element of $M^{-1}(x)$ currently under consideration. Thus, we do not need to traverse the list $M^{-1}(x)$ from the beginning each time we process a vertex. Algorithm 7 is an implementation of this procedure.

3.3.2 u and v are related as ancestor and descendant

Throughout this section it will be useful to keep in mind the situation depicted in Figure 5.

Proposition 3.12. *Let u, v, w be three vertices such that u is a descendant of v and v is a descendant of w. Then $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut if and only if $B(v) = B(u) \sqcup B(w)$.*

Proof. ($\Rightarrow$) Let $(x, y) \in B(v)$, and assume that $(x, y) \notin B(u)$. $(x, y) \in B(v)$ implies that y is a proper ancestor of v, and therefore a proper ancestor of u. Thus, $(x, y) \notin B(u)$ implies that x is not a descendant of u. Furthermore, $(x, y) \in B(v)$ implies that x is a descendant of v, and therefore a descendant of w. Now suppose, for the sake of contradiction, that y is not a proper ancestor of w. Then, $w \notin T[p(v), y)$. Now we see that, by removing the edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$ from the graph, v remains connected with $p(v)$ through the path $T[v, x], (x, y), T[y, p(v)]$ (since

Algorithm 7: Find all 3-cuts $\{(u, p(u)), (v, p(v)), (w, p(w))\}$, where w is an ancestor of u and v, and u, v are not related as ancestor and descendant

```
initialize an array currentVertex with n entries
foreach vertex x do currentVertex[x] ← x
for w ← n to w = 1 do
    m₁ ← M_low1(w), m₂ ← M_low2(w)
    if m₁ = ∅ or m₂ = ∅ then continue
    // find the lowest u in M⁻¹(m₁) which is greater than w
    u ← currentVertex[m₁]
    while nextM(u) ≠ ∅ and nextM(u) > w do u ← nextM(u)
    currentVertex[m₁] ← u
    // find the lowest v in M⁻¹(m₂) which is greater than w
    v ← currentVertex[m₂]
    while nextM(v) ≠ ∅ and nextM(v) > w do v ← nextM(v)
    currentVertex[m₂] ← v
    // check the condition in Lemma 3.10
    if b_count(w) = b_count(u) + b_count(v) and high(u) < w and high(v) < w then
        mark the triplet {(u, p(u)), (v, p(v)), (w, p(w))}
    end
end
```

$u, w \notin T[v, x] \cup T[p(v), y]$). This contradicts the fact that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Therefore, y is a proper ancestor of w, and thus $(x, y) \in B(w)$. Thus far we have established that $B(v) \subseteq B(u) \cup B(w)$. Now let $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of v. Suppose, for the sake of contradiction, that y is not a proper ancestor of v. Then, $v \notin T[p(u), y)$. Now we see that, by removing the edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$ from the graph, u remains connected with $p(u)$ through the path $T[u, x], (x, y), T[y, p(u)]$. This contradicts the fact that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Therefore, y is a proper ancestor of v, and thus $(x, y) \in B(v)$. This shows that $B(u) \subseteq B(v)$. Now let $(x, y) \in B(w)$. Then y is a proper ancestor of w, and therefore a proper ancestor of v. Suppose, for the sake of contradiction, that x is not a descendant of v. Then x is not a descendant of u, either, and so $u, v \notin T[x, w]$. Thus we see that, by removing the edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$ from the graph, w remains connected with $p(w)$ through the path $T[w, x], (x, y), T[y, p(w)]$. This contradicts the fact that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Therefore, x is a descendant of v, and thus $(x, y) \in B(v)$. This shows that $B(w) \subseteq B(v)$. Thus we have established that $B(u) \cup B(w) \subseteq B(v)$, and so we have $B(v) = B(u) \cup B(w)$.

Now suppose, for the sake of contradiction, that there is a back-edge $(x, y) \in B(u) \cap B(w)$. Since $B(u) \neq B(w)$ (for otherwise $u = w$), there must exist a back-edge (x', y') in $B(u) \setminus B(w)$ or in $B(w) \setminus B(u)$. Take the first case, first. Then, since $B(u) \subseteq B(v)$, y' is a proper ancestor of v. But since $(x', y') \notin B(w)$, y' cannot be a proper ancestor of w. Let P be a path connecting x' with x in $T(u)$. Then, by removing the tree-edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, w remains connected with $p(w)$ through the path $T[w, y'], (x', y'), P, (x, y), T[y, p(w)]$, which contradicts the assumption that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Now take the case $\exists (x', y') \in B(w) \setminus B(u)$. Then, since $B(w) \subseteq B(v)$, x' is a descendant of v. But since $(x', y') \notin B(u)$, x' cannot be a descendant of u. Let P be a path connecting y with y' in $T(r) \setminus T(w)$, and Q be a path connecting x' with $p(u)$ in $T(v) \setminus T(u)$. Then, by removing the tree-edges $(u, p(u))$, $(v, p(v))$ and $(w, p(w))$, u remains

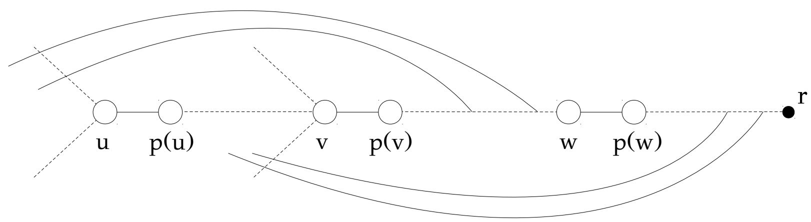

Figure 5: In this example we have $B(v) = B(u) \sqcup B(w)$. By removing the tree-edges $(u,p(u))$, $(v,p(v))$ and $(w,p(w))$, the graph becomes disconnected into two components: $T(u) \cup (T(w) \setminus T(v))$ and $(T(v) \setminus T(u)) \cup (T(r) \setminus T(w))$. (See also the "$\Leftarrow$" part of the proof of proposition 3.12.)

connected with $p(u)$ through the path $T[u,x],(x,y),P,(y',x'),Q$, which contradicts the assumption that $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ is a 3-cut. This shows that $B(u) \cap B(w) = \emptyset$. We conclude that $B(v) = B(u) \sqcup B(w)$.
($\Leftarrow$) Consider the sets of vertices $A = T(u)$, $B = T(v) \setminus T(u)$, $C = T(w) \setminus T(v)$ and $D = T(r) \setminus T(w)$. Since u is a descendant of v and v is a descendant of w, these sets are mutually disjoint. Now, since $B(u) \subset B(v)$ and $B(u) \cap B(w) = \emptyset$, every back-edge that starts from A ends either in A or in $T(v,w]$, and thus in C. Furthermore, every back-edge that starts from B and does not end in B, is a back-edge that starts from $T(v)$, but not from $T(u)$, and ends in a proper ancestor of v; thus, since $B(v) = B(u) \sqcup B(w)$, it ends in $T(w,r]$, and thus in D. Finally, every back-edge that starts from C must end in C, since $B(w) \subset B(v)$. Thus we see, that, by removing from the graph the tree-edges $(u,p(u))$, $(v,p(v))$ and $(w,p(w))$, the graph becomes separated into two parts: $A \cup C$ and $B \cup D$. ☐

Corollary 3.13. *If $(u,p(u))$, $(v,p(v))$ are two tree-edges, there is at most one w such that $\{(u,p(u)),(v,p(v)),(w,p($ is a 3-cut.*

Proof. This is a consequence of propositions 3.9 and 3.12. ☐

Here we distinguish two cases, depending on whether $M(v) = M(w)$ or $M(v) \neq M(w)$.

$M(v) \neq M(w)$

Lemma 3.14. *Let u be a descendant of v and v a descendant of w, and $M(v) \neq M(w)$. Then, $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ is a 3-cut if and only if: $M(w) = M_{low1}(v)$ and w is the greatest vertex with $M(w) = M_{low1}(v)$ which is lower than v, $M(u) = M_{low2}(v)$ and u is the lowest vertex with $M(u) = M_{low2}(v)$, $high(u) < v$ and $b\_count(v) = b\_count(u) + b\_count(w)$. (See Figure 6.)*

Proof. ($\Rightarrow$) By proposition 3.12, we have $B(v) = B(u) \sqcup B(w)$. This immediately establishes both $high(u) < v$ and $b\_count(v) = b\_count(u) + b\_count(w)$. Now, since $B(v) = B(u) \sqcup B(w)$, both $M(u)$ and $M(w)$ are descendants of $M(v)$. We will show that $M(u)$ and $M(w)$ are not related as ancestor and descendant. First, suppose that $M(u)$ is an ancestor of $M(w)$. Now let $(x,y) \in B(w)$.

Then x is a descendant of $M(w)$, and therefore a descendant of $M(u)$. Furthermore, y is a proper ancestor of w, and therefore a proper ancestor of u. This shows that $(x,y) \in B(u)$, contradicting the fact that $B(u) \cap B(w) = \emptyset$. Now suppose that $M(w)$ is an ancestor of $M(u)$. Let $(x,y) \in B(v)$. Since $B(v) = B(u) \sqcup B(w)$, x is a descendant of either $M(u)$ or $M(w)$. In either case, x is a descendant of w. Due to the generality of (x,y), this shows that $M(v)$ is a descendant of $M(w)$. Since $M(w)$ is also a descendant of $M(v)$, we get $M(w) = M(v)$, contradicting $M(w) \neq M(v)$. Thus we have established that $M(u)$ and $M(w)$ are not related as ancestor and descendant. Since $M(u)$ and $M(v)$ are descendants of $M(v)$, they must be proper descendants of $M(v)$. Now we will show that $M(u)$ and $M(w)$ are descendants of different children of $M(v)$. Suppose, for the sake of contradiction, that $M(u)$ and $M(w)$ are descendants of the same child c of $M(v)$. Then, there must exist a back-edge $(x,y) \in B(v)$ such that $x = M(v)$ or x is a descendant of a child of $M(v)$ different from c. (Otherwise, we would have that $M(v)$ is a descendant of c, which is absurd.) But this means that (x,y) is neither in $B(u)$ nor in $B(w)$, contradicting the fact that $B(v) = B(u) \sqcup B(w)$. Thus, one of $M(u)$ and $M(w)$ is a descendant of the *low1* child of $M(v)$, and the other is a descendant of the *low2* child of $M(v)$. Observe that there does not exist a back-edge $(x,y) \in B(u)$ such that $y = low(v)$, for this would imply that $(x,y) \in B(w)$ (since u is a descendant of w), and $B(u)$ does not meet $B(w)$. Thus, since $B(v) = B(u) \sqcup B(w)$, v gets its *low* point from $B(w)$. This shows that $M(w)$ is a descendant of the *low1* child of $M(v)$ and $M(u)$ is a descendant of the *low2* child of $M(v)$. Since $B(w) \subset B(v)$, we have that $M(w)$ is a descendant of $M_{low1}(v)$. Furthermore, since $B(v) = B(u) \sqcup B(w)$ and $M(u)$ is not a descendant of the *low1* child of $M(v)$, there are no back-edges (x,y) with x a descendant of the *low1* child of $M(v)$ and y a proper ancestor of v apart from those contained in $B(w)$. Thus, $M(w)$ is an ancestor of $M_{low1}(v)$, and $M_{low1}(v) = M(w)$ is established. With the same reasoning, we also get $M_{low2}(v) = M(u)$.

Now suppose, for the sake of contradiction, that there exists a vertex w' with $M(w') = M(w)$ and $v > w' > w$. This implies that $B(w) \subset B(w')$, and thus there is a back-edge $(x,y) \in B(w') \setminus B(w)$. Then x is a descendant of $M(w')$, and therefore a descendant of $M_{low1}(v)$. Furthermore, y is a proper ancestor of w', and therefore a proper ancestor of v. This shows that $(x,y) \in B(v)$, and therefore, since $B(v) = B(u) \sqcup B(w)$ and $(x,y) \notin B(w)$, we have $(x,y) \in B(u)$. But x is not a descendant of $M(u)$, since it is a descendant of $M(w)$ which is not related as ancestor or descendant with $M(u)$. That's a contradiction. Thus we have established that w is the greatest vertex with $M(w) = M_{low1}(v)$ which is lower than v. Finally, suppose for the sake of contradiction that there exists a vertex u' with $M(u') = M(u)$ and $u' < u$. This implies that $B(u') \subset B(u)$, and therefore there exists a back-edge $(x,y) \in B(u) \setminus B(u')$. Then, y is a proper ancestor of u and a descendant of u'. Since $high(u) < v$, we have $y < v$, and therefore u' is an ancestor of v. Now suppose that u' is an ancestor of w. Let $(x',y') \in B(u')$. Then x' is a descendant of $M(u')$, and therefore a descendant of $M(u)$, and therefore a descendant of u, and therefore a descendant of w. Furthermore, y' is a proper ancestor of u', and therefore a proper ancestor of w. This shows that $(x',y') \in B(w)$. But this cannot be the case, since $(x',y') \in B(u') \subset B(u)$ and $B(u) \cap B(w) = \emptyset$. Thus, u' is a descendant of w. Since u' is an ancestor of v, it is also an ancestor of $M_{low1}(v) = M(w)$. Thus, Lemma 2.4 implies that $M(u')$ is an ancestor of $M(w)$. But, since $M(u') = M(u)$, this contradicts the fact that $M(u)$ and $M(w)$ are not related as ancestor and descendant. Thus we have established that u is the lowest vertex with $M(u) = M_{low2}(v)$.

($\Leftarrow$) By proposition 3.12, it is sufficient to prove that $B(v) = B(u) \sqcup B(w)$. First, let $(x,y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of v. Furthermore, $y \leq high(u) < v$ implies that y is a proper ancestor of v. This shows that $B(u) \subseteq B(v)$. Now let $(x,y) \in B(w)$. Then y is a proper ancestor of w, and therefore a proper ancestor of v. Since $M(w) = M_{low1}(v)$, we have that x is a descendant of v. This shows that $B(w) \subseteq B(v)$. Thus we have $B(u) \cup B(w) \subseteq B(v)$. Since $M(u)$ and $M(w)$ are not related as ancestor and descendant (for they are descendants of different children

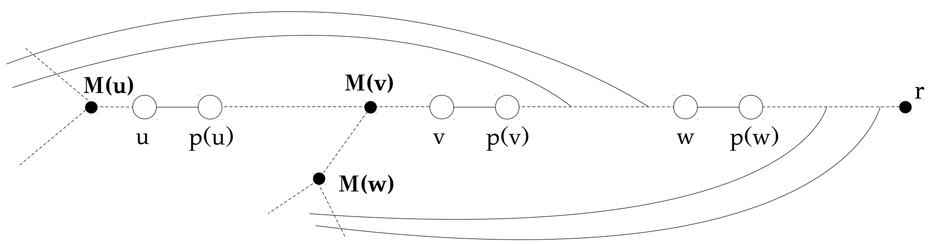

Figure 6: In this example we have $B(v) = B(u) \sqcup B(w)$. Observe that $M_{low1}(v) = M(w)$ and $M_{low2}(v) = M(u)$. u is the last vertex in $M^{-1}(M(u))$, and w is the greatest vertex in $M^{-1}(M(w))$ which is lower than v.

of $M(v)$), we have that $B(u) \cap B(w) = \emptyset$. In conjunction with $b\_count(v) = b\_count(u) + b\_count(w)$, from $B(u) \cup B(w) \subseteq B(v)$ and $B(u) \cap B(w) = \emptyset$ we conclude that $B(u) \sqcup B(w) = B(v)$. □

This lemma shows that, for every vertex v, there is at most one pair of vertices u, w, where u is a descendant of v, w is an ancestor of v, $M(v) \neq M(w)$, and $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. In particular, we have that w is the greatest vertex with $M(w) = M_{low1}(v)$ which is lower than v, u is the last vertex in $M^{-1}(M_{low2}(v))$, $high(u) < v$ and $b\_count(v) = b\_count(u) + b\_count(w)$. Thus, Algorithm 8 shows how we can compute all 3-cuts of this type. We only have to make sure that we can compute w without having to traverse the list $M^{-1}(M_{low1}(v))$ from the beginning, each time we process a vertex v. To achieve this, we process the vertices in a bottom-up fashion, and we keep in an array $currentM[x]$ the current element of $M^{-1}(x)$ under consideration, so that we do not need to traverse the list $M^{-1}(x)$ from the beginning each time we process a vertex.

$M(v) = M(w)$ Let w be a proper ancestor of v such that $M(v) = M(w)$. By corollary 3.13, there is at most one descendant u of v such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. In order to find this u (if it exists), we distinguish two cases, depending on whether $w = nextM(v)$ or $w \neq nextM(v)$. In any case, we will need the following lemma, which gives a necessary condition for the existence of u.

Lemma 3.15. *Let u, v, w be three vertices such that u is a descendant of v, v is a descendant of w, and $M(v) = M(w)$. Then, $B(v) = B(u) \sqcup B(w)$ only if $high(u) = high(v)$ and $nextM(u) = \emptyset$.*

Proof. Let $(x, y) \in B(u)$ be such that $y = high(u)$. Then, since $B(v) = B(u) \sqcup B(w)$, we have $(x, y) \in B(v)$, and so $y \leq high(v)$. Suppose for the sake of contradiction that $y \neq high(v)$. Then, since $B(v) = B(u) \sqcup B(w)$, there exists a $(x', y') \in B(w)$ such that $y' = high(v)$. Furthermore, since $y \neq high(v)$ and $(x, y) \in B(v)$, we have $y' > y$, which means that y is a proper ancestor of w. But then, since x is a descendant of u, it is also a descendant of w, and thus $(x, y) \in B(w)$, contradicting the fact that $B(u) \cap B(w) = \emptyset$. Thus we have shown that $high(u) = high(v)$.

Now suppose, for the sake of contradiction, that there exists a u' which is a proper ancestor of u with $M(u') = M(u)$. Then we have $B(u') \subset B(u)$. Now suppose, for the sake of contradiction, that u' is an ancestor of v. Suppose that u' is an ancestor of w. Let $(x, y) \in B(u')$. Then x

Algorithm 8: Find all 3-cuts $\{(u, p(u)), (v, p(v)), (w, p(w))\}$, where u is a descendant of v, v is a descendant of w, and $M(v) \neq M(w)$.

```
foreach vertex v do currentVertex[v] ← v
for v ← n to v = 1 do
    m1 ← M_low1(v), m2 ← M_low2(v)
    if m1 = ∅ or m2 = ∅ then continue
    // find the greatest w in M^{-1}(m1) which is lower than v
    w ← currentVertex(m1)
    while w ≠ ∅ and w ≥ v do w ← nextM(w)
    currentVertex[m1] ← w
    // u is the last element of M^{-1}(m2)
    u ← lastM(m2)
    // check the condition in Lemma 3.14
    if w ≠ ∅ and high(u) < v and b_count(v) = b_count(u) + b_count(w) then
        mark the triplet {(u, p(u)), (v, p(v)), (w, p(w))}
    end
end
```

is a descendant of $M(u')$, and therefore a descendant of $M(u)$, and therefore a descendant of u, and therefore a descendant of w. Furthermore, y is a proper ancestor of u', and therefore a proper ancestor of w. This means that $(x, y) \in B(w)$, and thus we have $B(u') \subseteq B(w)$. But this contradicts $B(u) \cap B(w) = \emptyset$, since $B(u') \subset B(u)$. Thus, we have that u' is a descendant of w. Then, since u' is an ancestor of v, it is also an ancestor of $M(v) = M(w)$, and thus, by Lemma 2.4, $M(u') = M(u)$ is an ancestor of $M(v)$. Since $B(v) = B(u) \sqcup B(w)$, we have that $M(v)$ is an ancestor of $M(u)$, and thus $M(u) = M(v)$. In conjunction with $high(u) = high(v)$, this implies that $B(v) = B(u)$, contradicting the fact that the graph is 3-edge-connected. Thus, we have that u' is not an ancestor of v. Since v and u' have u as a common descendant, we infer that u' is a descendant of v. Now, since $B(u') \subset B(u)$, we have that there exists a back-edge $(x, y) \in B(u) \setminus B(u')$. Then, y is descendant of u', and therefore a descendant of v. But this means that $(x, y) \notin B(v)$, contradicting the fact that $B(u) \subset B(v)$. We conclude that there is not $u' \in M^{-1}(M(u))$ which is a proper ancestor of u. □

Case $w = nextM(v)$. Now we will show how to find, for every vertex v, the unique u (if it exists) which is a descendant of v and such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut, where $w = nextM(v)$. Obviously, the number of 3-cuts of this type is $O(n)$. According to Lemma 3.15, $high(u) = high(v)$, and therefore it is sufficient to seek this u in $high^{-1}(high(v))$.

Proposition 3.16. *Let $h = high(v)$ and $w = nextM(v)$, and suppose that the list $high^{-1}(h)$ is sorted in decreasing order. Then, u is a descendant of v such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut if and only if u is a predecessor of v in $high^{-1}(h)$, $nextM(u) = \emptyset$, $low(u) \geq w$, $b\_count(u) = b\_count(v) - b\_count(w)$, and all elements of $high^{-1}(h)$ between u and v are ancestors of u.*

Proof. ($\Rightarrow$) By proposition 3.12, we have $B(v) = B(u) \sqcup B(w)$. This shows that $b\_count(u) = b\_count(v) - b\_count(w)$ and $low(u) \geq w$ (for if we had $low(u) < w$, then $B(u)$ would intersect $B(w)$). Lemma 3.15 shows that $high(u) = high(v)$ and $nextM(u) = \emptyset$. Since u is a descendant of v, it is greater than v, and thus it is a predecessor of v in $high^{-1}(x)$. Now suppose that there exists a $u' \in high^{-1}(x)$ which is lower than u and greater than v, but it is not an ancestor of u.

Since u is a descendant of v, $v < u' < u$ implies that u' is also a descendant of v. Let (x, h) be a back-edge with x a descendant of u'. Then x is a also a descendant of v, and thus $(x, h) \in B(v)$. But since u' is not a descendant of u, x cannot be a descendant of u either, and so $(x, h) \in B(v)$ and $B(v) = B(u) \sqcup B(w)$ both imply that $(x, h) \in B(w)$. However, $h = \mathit{high}(u) \geq \mathit{low}(u) \geq w$. A contradiction.
($\Leftarrow$) By proposition 3.12, it is sufficient to show that $B(v) = B(u) \sqcup B(w)$. Let $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of v. Furthermore, since $\mathit{high}(u) = \mathit{high}(v)$, we have that y is a proper ancestor of v. This shows that $(x, y) \in B(v)$, and thus we have $B(u) \subseteq B(v)$. Now, since $M(v) = M(w)$ and $w = \mathit{nextM}(v) < v$, we have that $B(w) \subset B(v)$. Thus we have established that $B(u) \cup B(w) \subseteq B(v)$. Now observe that $B(u) \cap B(w) = \emptyset$: for if $(x, y) \in B(u)$, then $y \geq \mathit{low}(u)$, and we have assumed that $\mathit{low}(u) \geq w$; thus, $(x, y) \notin B(w)$. Now, since $\mathit{b\_count}(u) = \mathit{b\_count}(v) - \mathit{b\_count}(w)$ and $B(u) \cup B(w) \subseteq B(v)$ and $B(u) \cap B(w) = \emptyset$, we conclude that $B(v) = B(u) \sqcup B(w)$. ☐

Now let h be a vertex. Based on proposition 3.16, we will show how to find, for every v in the decreasingly sorted list $\mathit{high}^{-1}(h)$, the unique vertex $u \in \mathit{high}^{-1}(h)$ (if it exists) such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut, where $w = \mathit{nextM}(v)$. To do this, we need an array A of size m (the number of edges of the graph), and a stack S. We begin by traversing the list $\mathit{high}^{-1}(h)$ from its first element, and every u we meet that satisfies $\mathit{nextM}(u) = \emptyset$ and is an ancestor of its predecessor (or the first element of the list) we push it in S and also store it in $A[\mathit{b\_count}(u)]$. If u is not an ancestor of its predecessor, we set $A[z] = \emptyset$, for every $z \in S$, while we pop out all elements from S; then we push u in S and also store it in $A[\mathit{b\_count}(u)]$. Now, if we meet a vertex v that satisfies $\mathit{nextM}(v) \neq \emptyset$ and is ancestor of its predecessor, we check whether the entry $u = A[\mathit{b\_count}(v) - \mathit{b\_count}(\mathit{nextM}(v))]$ is not $\emptyset$, and if $\mathit{low}(u) \geq \mathit{nextM}(v)$ we mark the triplet $\{(u, p(u)), (v, p(v)), (\mathit{nextM}(v), p(\mathit{nextM}(v)))\}$ (observe that u satisfies all conditions of proposition 3.16). If v is not an ancestor of the top element of S, we set $A[u] = \emptyset$, for every $u \in S$, while we pop out all elements from S. In any case, we keep traversing the list, following the same procedure, until we reach its end. This process is implemented in Algorithm 9.

Case $w \neq \mathit{nextM}(v)$. Now we will show how to find, for every vertex v, the set of all u which are descendants of v with the property that there exists a w with $M(w) = M(v)$ and $w < \mathit{nextM}(v)$, such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. Let $U(v)$ denote this set. (An illustration is given in Figure 7.) According to Lemma 3.15, for every $u \in U(v)$ we have $\mathit{high}(u) = \mathit{high}(v)$, and therefore it is sufficient to seek those u in $\mathit{high}^{-1}(\mathit{high}(v))$.

To do this, we use a stack $\mathit{stackU}[v]$, for every vertex v, in which we store vertices u from $\mathit{high}^{-1}(\mathit{high}(v))$. By the time we have filled all stacks $\mathit{stackU}[v]$, the following three properties will be satisfied: (1) for every vertex v, $U(v) \subseteq \mathit{stackU}[v]$, (2) if $v \neq v'$, then $\mathit{stackU}[v] \cap \mathit{stackU}[v'] = \emptyset$, and (3) every u in $\mathit{stackU}[v]$ is a descendant of its successors in $\mathit{stackU}[v]$. The contents of $\mathit{stackU}[v]$ will be all those u satisfying the necessary condition described in the following lemma.

Lemma 3.17. *Let $h = \mathit{high}(v)$, and assume that the list $\mathit{high}^{-1}(h)$ is sorted in decreasing order. Then, $u \in U(v)$ only if u is a predecessor of v in $\mathit{high}^{-1}(h)$ such that $\mathit{nextM}(u) = \emptyset$, $\mathit{low}(u) < \mathit{nextM}(v)$, $\mathit{low}(u) \geq \mathit{lastM}(v)$, and all elements of $\mathit{high}^{-1}(h)$ between u and v are ancestors of u.*

Proof. $u \in U(v)$ means that u is a descendant of v and there is an ancestor w of v such that $M(v) = M(w)$, $w \neq \mathit{nextM}(v)$, and $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. By proposition 3.12, we have $B(v) = B(u) \sqcup B(w)$. From this we infer that $\mathit{low}(u) \geq w$ (for otherwise, since u is a descendant of w, we would have that $B(u)$ meets $B(w)$). This shows that $\mathit{low}(u) \geq \mathit{lastM}(v)$. Lemma 3.15 implies that $\mathit{high}(u) = \mathit{high}(v)$ and $\mathit{nextM}(u) = \emptyset$. Furthermore, since u is a descendant

Algorithm 9: Find all 3-cuts $\{(u,p(u)),(v,p(v)),(w,p(w))\}$, where u is a descendant of v and $w = nextM(v)$.

```
initialize an array A with m entries (where m is the number of edges of the graph)
initialize a stack S
sort the elements of every list high^{-1}(h), for every vertex h, in decreasing order
foreach vertex h do
    u ← first element of high^{-1}(h)
    while u ≠ ∅ do
        z ← next element of high^{-1}(h)
        if z = ∅ then break
        if z is not an ancestor of u then
            while S is not empty do
                u' ← S.pop()
                A[b_count(u')] ← ∅
            end
        end
        if nextM(z) = ∅ then
            S.push(z)
            A[b_count(z)] ← z
        end
        else if nextM(z) ≠ ∅ then
            v ← z, w ← nextM(v)
            if A[b_count(v) − b_count(w)] ≠ ∅ then
                u ← A[b_count(v) − b_count(w)]
                if low(u) ≥ w then
                    mark the triplet {(u,p(u)),(v,p(v)),(w,p(w))}
                end
            end
        end
        u ← z
    end
end
```

of v, it is greater than v, and thus it is a predecessor of v in $high^{-1}(h)$. Now suppose, for the sake of contradiction, that $low(u) \geq nextM(v)$. Since there is a $w < nextM(v)$ such that $M(w) = M(v)$, there must exist a back-edge $(x,y) \in B(v)$ with $y \in T(nextM(v), w]$. Since $low(u) \geq nextM(v)$, it cannot be the case that $(x,y) \in B(u)$, and therefore $B(v) = B(u) \sqcup B(w)$ implies that $(x,y) \in B(w)$, which is absurd, since $y \geq w$. Thus, $low(u) < nextM(v)$. Finally, suppose, for the sake of contradiction, that there exists a $u' \in high^{-1}(h)$ which is lower than u and greater than v, but it is not an ancestor of u. Since u is a descendant of v, $v < u' < u$ implies that u' is also a descendant of v. Let (x,h) be a back-edge with x a descendant of u'. Then x is a also a descendant of v, and thus $(x,h) \in B(v)$. But since u' and u are not related as ancestor or descendant, x cannot be a descendant of u. Thus, $(x,h) \notin B(u)$. Since $(x,h) \in B(v)$ and $B(v) = B(u) \sqcup B(w)$, this implies that $(x,h) \in B(w)$. However, $h = high(u) \geq low(u) \geq w$. A contradiction. □

Thus, $stackU[v]$ contains all u that are predecessors of v in $high^{-1}(high(v))$ and satisfy $nextM(u) =$

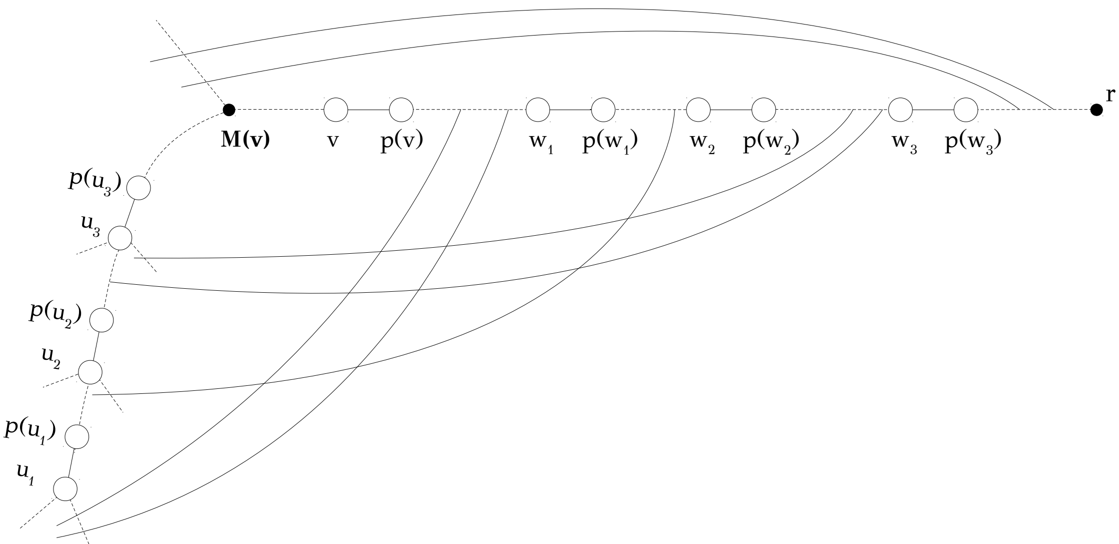

Figure 7: In this example we have $M(v) = M(w_1) = M(w_2) = M(w_3)$, $U(v) = \{u_1, u_2, u_3\}$, and the triplets $\{(u_i, p(u_i)), (v, p(v)), (w_i, p(w_i))\}$, for $i \in \{1, 2, 3\}$, are 3-cuts. Observe that all $\{u_1, u_2, u_3\}$ are related as ancestor and descendant. This property is proved in Lemma 3.17. Furthermore, all $u \in U(v)$ have $high(u) = high(v)$.

$\emptyset$, $low(u) < nextM(v)$, $low(u) \geq lastM(v)$ and all elements of $high^{-1}(high(v))$ between u and v are ancestors of u. By Lemma 3.17, property (1) of the stacks $stackU[v]$ is satisfied. The following lemma shows that property (2) is also satisfied.

Lemma 3.18. *Let v, v' be two vertices such that v' is a proper ancestor of v with $high(v') = high(v)$, and let $u \in stackU[v]$. Then $u \notin stackU[v']$.*

Proof. First observe that the stacks $stackU[v]$ and $stackU[v']$ are non-empty only if $nextM(v) \neq \emptyset$ and $nextM(v') \neq \emptyset$. Now, since $high(v') = high(v)$, by Lemma 3.20, we have that $nextM(v) < lastM(v')$. Since $u \in stackU[v]$, it has $low(u) < nextM(v)$. But then $low(u) < lastM(v')$, and so $u \notin stackU[v']$. □

This implies that the total number of elements in all stacks $stackU[v]$ (by the time we have filled them) is $O(n)$. Now let h be a vertex, and let us show how to fill the stacks $stackU[v]$, for all v in the decreasingly sorted list $high^{-1}(h)$. To do this, we will need a stack S. We begin traversing the list $high^{-1}(h)$ from its first element, and when we process a vertex u such that $nextM(u) = \emptyset$ we push it in S if it is an ancestor of its predecessor (or the first elements of the list). Otherwise, we drop all elements from S, push u in S, and keep traversing the list. When we meet a vertex v that satisfies $nextM(v) \neq \emptyset$ and is also an ancestor of its predecessor, we check whether the top element u of S satisfies $low(u) < lastM(v)$, in which case we start popping elements out of S, until the top element u of S (if S is not left empty) satisfies $low(u) \geq lastM(v)$. Then, as long as the top element u of S satisfies $low(u) < nextM(v)$, we repeatedly pop out the top element from S and push it in $stackU[v]$. If v is not an ancestor of its predecessor, we drop all elements from S. In any case, we keep traversing the list, following the same procedure, until we reach its end. This process is implemented in Algorithm 10. Property (3) of the stacks $stackU$ is satisfied due to the way we fill them with this algorithm. To prove the correctness of Algorithm 10 - i.e., that by the time we reach the end of $high^{-1}(h)$, every stack $stackU[v]$, for every $v \in high^{-1}(h)$, contains all elements u satisfying the necessary condition in Lemma 3.17 -, we need the following two lemmata.

Lemma 3.19. *If u' is an ancestor of u with $high(u) = high(u')$, then $low(u') \leq low(u)$.*

Proof. Let $(x, y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of u'. Furthermore, $y \leq high(u) = high(u')$, and therefore y is a proper ancestor of u'. This shows that $(x, y) \in B(u')$, and thus we have $B(u) \subseteq B(u')$. $low(u') \leq low(u)$ is an immediate consequence of this fact. □

Lemma 3.20. *Let v, v' be two vertices such that v' is a proper ancestor of v, $nextM(v) \neq \emptyset$, $nextM(v') \neq \emptyset$, and $high(v') = high(v)$. Then, $nextM(v) < lastM(v')$.*

Proof. Let $(x, y) \in B(v)$. Then x is a descendant of v, and therefore a descendant of v'. Furthermore, since $y \leq high(v)$ and $high(v) = high(v')$ and $high(v') < v'$, we have that y is a proper ancestor of v'. This shows that $(x, y) \in B(v')$, and thus $B(v) \subseteq B(v')$. From this we infer that $M(v)$ is a descendant of $M(v')$. Now, since $M(nextM(v)) = M(v)$ and $nextM(v) < v$, we have that $B(nextM(v)) \subset B(v)$. This means that there exists a back-edge (x, y) such that x is a descendant of $M(v)$ and y is a proper ancestor of v but not a proper ancestor of $nextM(v)$. Then, since $(x, y) \in B(v)$, we have $y \leq high(v)$, and so $high(v)$ is not a proper ancestor of $nextM(v)$, and thus $nextM(v)$ is an ancestor of $high(v)$. Since $high(v) = high(v')$ and $high(v')$ is a proper ancestor of v', we infer that $nextM(v)$ is a proper ancestor of v'. Now suppose, for the sake of contradiction, that $lastM(v')$ is an ancestor of $nextM(v)$. Let $(x, y) \in B(lastM(v'))$. Then, x is a descendant of $M(lastM(v'))$, and thus a descendant of $M(v')$, and thus a descendant of v', and thus a descendant of $nextM(v)$. Furthermore, y is a proper ancestor of $lastM(v')$, and therefore a proper ancestor of $nextM(v)$. This shows that $(x, y) \in B(nextM(v))$, and thus we have $B(lastM(v')) \subseteq B(nextM(v))$. From this we infer that $M(lastM(v'))$ is a descendant of $M(nextM(v))$. But $M(lastM(v')) = M(v')$ and $M(nextM(v)) = M(v)$. Thus, $M(v')$ is a descendant of $M(v)$. Since $M(v)$ is a descendant of $M(v')$, we conclude that $M(v') = M(v)$. But this implies, in conjunction with $high(v') = high(v)$, that $B(v) = B(v')$, contradicting the fact that the graph is 3-edge-connected. This shows that $nextM(v)$ is a proper ancestor of $lastM(v')$. □

Now, to prove the correctness of Algorithm 10, we have to show that the elements we push into $stackU[v]$ satisfy the necessary condition in Lemma 3.17, and the elements we pop out from S do not satisfy this condition either for v or for any successor of v in the list $high^{-1}(h)$. So, let v be a vertex in $high^{-1}(h)$ such that $nextM(v) \neq \emptyset$, and let v' be a successor of v in $high^{-1}(h)$ such that $nextM(v') \neq \emptyset$. Now, when we meet v as we traverse $high^{-1}(x)$, we pop out the top elements u from S that have $low(u) < lastM(v)$. By the definition of $stackU[v]$, these are not included in $stackU[v]$. Now, by Lemma 3.20, we have $nextM(v) < lastM(v')$. Since $low(u) < lastM(v) \leq nextM(v)$, we have $low(u) < lastM(v')$, and thus u is not in $stackU[v']$ either, so it does not matter that we pop those u out of S. Then, once we reach a $\tilde{u}$ in S that satisfies $low(\tilde{u}) \geq lastM(v)$, we pop out the top elements u of S that have $low(u) < nextM(v)$, and push them into $stackU[v]$. This is according to the definition of $stackU[v]$. Since $nextM(v) < lastM(v')$ and $low(u) < nextM(v)$, we have $low(u) < lastM(v')$, and so, again, these u are not included in $stackU[v']$, and thus it does not matter that we pop them out of S. Now, when we reach a u in S that has $low(u) \geq nextM(v)$, we can be certain, by Lemma 3.19, that no u' in S has $low(u') < nextM(v)$, since all elements of S are descendants of u (by the way we fill the stack S), and thus they have $low(u') \geq low(u) \geq nextM(v)$. Then it is proper to move on to the next element of $high^{-1}(h)$.

Lemma 3.21. *Let v be a vertex and u, u' two elements in $stackU[v]$, where u is a predecessor of u' in $stackU[v]$. Then, $low(u') \leq low(u)$.*

Proof. Since $u, u' \in stackU[v]$, we have $high(u) = high(v) = high(u')$. Since u is a predecessor of u' in $stackU[v]$, by property (3) of $stackU[v]$ we have that u is a descendant of u'. Thus, by Lemma 3.19, we get $low(u') \leq low(u)$. □

The next lemma is the basis to find all 3-cuts of the form $\{(u, p(u)), (v, p(v)), (w, p(w))\}$, where u is a descendant of v, $M(v) = M(w)$, and $w \neq nextM(v)$.

Lemma 3.22. *Let u be a vertex in $stackU[v]$ and w a proper ancestor of v such that $M(w) = M(v)$. Then, if $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut, we have that $b\_count(v) = b\_count(u) + b\_count(w)$ and w is the greatest element of $M^{-1}(M(v))$ such that $w \leq low(u)$. Conversely, if $b\_count(v) = b\_count(u) + b\_count(w)$ and $w \leq low(u)$, then $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut.*

Proof. ($\Rightarrow$) By proposition 3.12, we have $B(v) = B(u) \sqcup B(w)$. This explains both $b\_count(v) = b\_count(u) + b\_count(w)$ and $w \leq low(u)$. (For if we had $low(u) < w$, then, since u is a descendant of w, $B(u)$ would meet $B(w)$.) Now suppose, for the sake of contradiction, that there is a vertex w' such that $M(w') = M(v)$ and $w < w' \leq low(u)$. Since $B(v) = B(u) \sqcup B(w)$, we have that $low(u) < v$, and therefore $w' < v$. Since $M(w') = M(v)$, this means that $B(w') \subset B(v)$. Furthermore, since $M(w) = M(w')$ and $w < w'$, we infer that $B(w) \subset B(w')$, and therefore there exists a back-edge $(x, y) \in B(w') \setminus B(w)$. Then, by $B(w') \subset B(v)$, we have that $(x, y) \in B(v)$, and $B(v) = B(u) \sqcup B(w)$ implies that $(x, y) \in B(u)$ or $(x, y) \in B(w)$. Since $(x, y) \notin B(w)$, $(x, y) \in B(u)$ is the only option left. But y is a proper ancestor of w', and therefore a proper ancestor of $low(u)$ (since $w' \leq low(u)$).

Algorithm 10: Fill all stacks $stackU[v]$, for all vertices v

```
initialize a stack S
foreach vertex v do initialize a stack stackU[v]
foreach vertex h do
    u ← first element of high^{-1}(h)
    while u ≠ ∅ do
        z ← next element of high^{-1}(h)
        if z = ∅ then break
        if z is not an ancestor of u then
            pop out all elements from S
        end
        if nextM(z) = ∅ then
            S.push(z)
        end
        else if nextM(z) ≠ ∅ then
            while low(S.top()) < lastM(v) do S.pop()
            while low(S.top()) < nextM(v) do
                u ← S.pop()
                stackU[v].push(u)
            end
        end
        u ← z
    end
end
```

This implies that $(x,y) \notin B(u)$, which is absurd. We conclude that w is the greatest element of $M^{-1}(M(v))$ such that $w \leq low(u)$.
($\Leftarrow$) By proposition 3.12, is is sufficient to show that $B(v) = B(u) \sqcup B(w)$. $u \in stackU[v]$ implies that u is a descendant of v such that $high(u) = high(v)$. Now let $(x,y) \in B(u)$. Then x is a descendant of u, and therefore a descendant of v. Furthermore, $y \leq high(u) = high(v)$, and therefore y is a proper ancestor of v. This shows that $(x,y) \in B(v)$, and thus we have $B(u) \subseteq B(v)$. Since $M(w) = M(v)$ and $w < v$, we have $B(w) \subset B(v)$. Thus we have established that $B(u) \cup B(w) \subseteq B(v)$. Notice that no $(x,y) \in B(u)$ is contained in $B(w)$, since $y \geq low(u) \geq w$, and thus y is not a proper ancestor of w. Thus we have $B(u) \cap B(w) = \emptyset$. Now $B(v) = B(u) \sqcup B(w)$ follows from $B(u) \cup B(w) \subseteq B(v)$, $B(u) \cap B(w) = \emptyset$ and $b\_count(v) = b\_count(u) + b\_count(w)$. □

Now our goal is to find, for every $u \in stackU[v]$, for every vertex v, the vertex w (if it exists) which has $M(w) = M(v)$ and $w < nextM(v)$, and is such that $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ is a 3-cut. By Lemma 3.22, w has the property that it is the greatest vertex in $M^{-1}(M(v))$ which has $w \leq low(u)$. Let us describe a simple method to find the w with this property, which will give us the intuition to provide a linear-time algorithm for our problem. So let v be a vertex, $m = M(v)$, and u be a vertex in $stackU[v]$. A simple idea is to start from v and keep traversing the list $M^{-1}(m)$, through the pointers $nextM$, until we reach a $w \in M^{-1}(m)$ such that $w \leq low(u)$. The problem here is that we may have to pass from the same elements of $M^{-1}(m)$ an excessive amount of times (depending on the number of elements in $stackU[v]$). We can remedy this by keeping in a variable $lowestW$ the w that we reached the last time we processed a $u \in stackU[v]$. Then, when we process the successor of u in $stackU[v]$, we begin the search in $M^{-1}(m)$ from $lowestW$. This will work, since the every $u \in stackU[v]$ is a descendant of its successor u' in $stackU[v]$ (due to the way we have filled the stacks $stackU$ with Algorithm 10), and we have $high(u) = high(u')$, and therefore, by Lemma 3.19, $low(u') \leq low(u)$. However, this is, again, not a linear-time procedure, since, for every vertex v, when we start processing the first vertex in $stackU[v]$, we begin traversing the list $M^{-1}(M(v))$ from v, and therefore, every time we process a vertex v' with $M(v') = M(v)$, we may have to pass again from the same vertices that we passed from during the processing of v, exceeding the time bound in total. Now, to achieve linear time, we process the vertices from the lowest to the highest, and, for every v that we process, we keep in a variable $lowestW[v]$ the w that we reached the last time we processed a $u \in stackU[v]$. Then, when we have to process a $u \in stackU[v]$, we traverse the list $M^{-1}(M(v))$ through the pointers $lowestW$, starting from $lowestW[v]$. (Initially, we set every $lowestW[v]$ to $nextM(v)$.) Thus we perform a kind of path-compression method, which is shown Algorithm 11. The next three lemmata will be used in proving the correctness and linear complexity of Algorithm 11.

Lemma 3.23. *Let v be a vertex and $u \in stackU[v]$. When we reach line 8 during the processing of u, we have that w is a vertex in $M^{-1}(M(v))$ such that $w \leq low(u)$ and $w \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $w < v' < v$ and $u' \in stackU[v']\}$.*

Proof. First observe that, during the processing of a vertex v, the variables w and $lowestW[v]$ are members of $M^{-1}(M(v))$, and w is an ancestor of v while $lowestW[v]$ is a proper ancestor of v. (It is easy to see this inductively. For if this holds for all vertices $v' < v$, then it is also true for v, since the **while** loop in line 7 assigns w to $lowestW[w]$, and w is assumed to be an ancestor of v with $M(w) = M(v)$, and thus $lowestW[w]$ is also an ancestor of v with $M(lowestW[w]) = M(v)$, due to the inductive hypothesis.) Then it is obvious that, when we reach line 8 during the processing of $u \in stackU[v]$, we have that $M(w) = M(v)$ and $w \leq low(u)$, since the **while** loop in line 7 terminates precisely when such a w is found. Now we will show that, when we process a $u \in stackU[v]$, every time w is assigned $lowestW[w]$ during the execution of the **while** loop in line 7, we have $w \leq low(u')$, for every $u' \in stackU[v']$, for every v' with $M(v') = M(v)$ and $w < v' < v$. It is easy to see this inductively. Suppose, then, that this was the case for every vertex that we processed before v, for every predecessor of u in $stackU[v]$ that we already processed, and for every step of the **while** loop in line 7 in the processing of u so far. Thus, now w has the property that $w \leq low(u')$, for every $u' \in stackU[v']$, for every v' with $M(v') = M(v)$ and $w < v' < v$. So let us perform $w \leftarrow lowestW[w]$ once more (which means that we still have $w > low(u)$), and let $\tilde{w}$ be the current value of w, to distinguish it from the previous one which we will denote simply as w. Now, due to the inductive hypothesis, we have that $\tilde{w} \leq low(u')$ for every $u' \in stackU[v']$, for every v' with $M(v') = M(v)$ and $\tilde{w} < v' < w$. We also have (again, due to the inductive hypothesis) that $w \leq low(u')$ for every $u' \in stackU[v']$, for every v' with $M(v') = M(v)$ and $w < v' < v$. Since $\tilde{w} < w$, we thus have $\tilde{w} \leq low(u')$, for every $u' \in stackU[v']$, for every v' with $M(v') = M(v)$ and $\tilde{w} < v' < w$ or $w < v' < v$. Thus we only have to consider the case $v' = w$, and prove that every $u' \in stackU[w]$ satisfies $\tilde{w} \leq low(u')$. Observe that $lowestW[w]$ was updated for the last time in line 8 when we were processing the last element $\tilde{u}$ of $stackU[w]$. Then, since $\tilde{w} = lowestW[w]$, due to the inductive hypothesis we have that $\tilde{w} \leq low(\tilde{u})$. Since every $u' \in stackU[w]$ has $high(u') = high(\tilde{u})$ and $\tilde{u}$ is an ancestor of its predecessors in $stackU[w]$ (due to the way we have filled the stacks $stackU$ with Algorithm 10), by Lemma 3.19 we have that $low(\tilde{u}) \leq low(u')$, and therefore $\tilde{w} \leq low(u')$. Thus we have shown that $\tilde{w} \leq low(u')$, for every $u' \in stackU[v']$, for every v' with $M(v') = M(v)$ and $\tilde{w} < v' < v$. ∎

Lemma 3.24. *Let v be a vertex and $u \in stackU[v]$. When we reach line 8 during the processing of u, we have that w is the greatest vertex in $M^{-1}(M(v))$ such that $w \leq low(u)$ and $w \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $w < v' < v$ and $u' \in stackU[v']\}$.*

Proof. We will prove this lemma by induction. Let's assume, then, that, for every vertex $v' \leq v$, and every $u' \in stackU[v']$ that we processed so far, whenever we reached line 8 w was the greatest vertex with $M(w) = M(v')$ such that $w \leq low(u)$ and $w \leq min\{low(u'') \mid \exists v''$ with $M(v'') = M(v')$, $w < v'' < v'$ and $u'' \in stackU[v'']\}$. Now let u be the next element of $stackU[v]$ that we process. Let $\tilde{w}$ be the greatest vertex with $M(\tilde{w}) = M(v)$ such that $\tilde{w} \leq low(u)$ and $\tilde{w} \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $\tilde{w} < v' < v$ and $u' \in stackU[v']\}$. (The existence of such a $\tilde{w}$ is guaranteed by Lemma 3.23.) Let w be the last vertex during the execution of the **while** loop in line 7 that had $w > low(u)$, and let $w' = lowestW[w]$. Then we have that $w' = lowestW[w] \leq low(u)$, and the **while** loop terminates here. We will show that $w' = \tilde{w}$. We distinguish two cases, depending on whether $w' = nextM(w)$ or $w' \neq nextM(w)$. In the first case, we have that $w > low(u)$, but $nextM(w) \leq low(u)$. Thus, $w' = nextM(w)$ is the greatest vertex with $M(w') = M(v)$ such that $w' \leq low(u)$, and so we have $w' = \tilde{w}$ (since w' satisfies also $w' \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $w < v' < v$ and $u' \in stackU[v']\}$, by Lemma 3.23). Now, if $w' \neq nextM(w)$, this means, due to the inductive hypothesis (and since $w' = lowestW[w]$), that w' is the greatest vertex with $M(w') = M(w)$ such that $w' \leq low(\tilde{u})$ and $w' \leq min\{low(u') \mid \exists v'$ with $M(v') = M(w)$, $w' < v' < w$ and $u' \in stackU[v']\}$, where $\tilde{u}$ is the last element in $stackU[w]$. Now, since $\tilde{w}$ satisfies $\tilde{w} \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $\tilde{w} < v' < v$ and $u' \in stackU[v']\}$ and $\tilde{w} < w < v$, we have $\tilde{w} \leq low(\tilde{u})$ and $\tilde{w} \leq min\{low(u') \mid \exists v'$ with $M(v') = M(w)$, $\tilde{w} < v' < w$ and $u' \in stackU[v']\}$. Thus, $\tilde{w}$ cannot be greater than w', and so we have $w' \geq \tilde{w}$. Since $w' \leq low(u)$, and, as a consequence of Lemma 3.23, $w' \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $w' < v' < v$ and $u' \in stackU[v']\}$, it must be the case that $w' = \tilde{w}$. □

Lemma 3.25. *Let $\{(u, p(u)), (v, p(v)), (w, p(w))\}$ be a 3-cut where u is a descendant of v, v is a descendant of w with $M(v) = M(w)$, and $w \neq nextM(v)$. Then, w is the greatest vertex in $M^{-1}(M(v))$ such that $w \leq low(u)$ and $w \leq min\{low(u') \mid \exists v'$ with $M(v') = M(v)$, $w < v' < v$ and $u' \in stackU[v']\}$.*

Proof. Suppose, for the sake of contradiction, that there exists a vertex v' with $M(v') = M(v)$ and $w < v' < v$, such that there exists a $u' \in stackU[v']$ with $low(u') < w$. Since $u' \in stackU[v']$, we have that u' is a proper descendant of v' with $high(u') = high(v')$. Let $(x, y) \in B(u')$ (of course, $B(u')$ is not empty, since the graph is 3-edge-connected). Then x is a descendant of u', and therefore a descendant of v'. Furthermore, $y \leq high(u') = high(v')$, and therefore y is a proper ancestor of v'. This shows that $(x, y) \in B(v')$. Thus we have $B(u') \subset B(v')$. Since $M(v') = M(v)$ and $v' < v$, we have $B(v') \subset B(v)$. Thus, $B(u') \subset B(v)$. Now we will prove that u' is not related as ancestor or descendant with u. First, since $low(u') < w \leq low(u)$, it cannot be the case that u' is a descendant of u (for a back-edge $(x, low(u')) \in B(u')$ would also be a back-edge in $B(u)$, and thus we would have $low(u) \leq low(u')$, which is a absurd). Suppose, then, that u' is an ancestor of u. Since v' is a proper ancestor of v with $M(v') = M(v)$, we must have $high(v') < high(v)$; and since $high(u') = high(v')$, we therefore have $high(u') < high(v)$. This means that u' (which is related as ancestor or descendant with v, since we supposed it is an ancestor of u) is a proper ancestor of v, and therefore a proper ancestor of $M(v)$. Since, then, u' is a descendant v' and $M(v') = M(v)$, by Lemma 2.4 we have that $M(u')$ is an ancestor of $M(v)$. But $B(u') \subset B(v)$ implies that $M(u')$ is a descendant of $M(v)$, and therefore $M(u') = M(v)$. Since $M(v) = M(v')$ and $high(v') = high(u')$, we get that $B(u') = B(v')$, which implies that $v' = u'$ - a contradiction. Thus we have shown that u' is not related as ancestor or descendant with u.

Now let (x,y), with $y = high(u')$, be a back-edge in $B(u')$. Then we have $(x,y) \in B(v)$. By proposition 3.12, we have $B(v) = B(u) \sqcup B(w)$, and therefore $(x,y) \in B(u)$ or $(x,y) \in B(w)$. Since u' is not related as ancestor of descendant with u, it cannot be the case that x (which is a descendant of u') is a descendant of u, and therefore $(x,y) \in B(u)$ is rejected. Now, since $B(u') \subset B(v')$, we have $(x,y) \in B(v')$. Since $M(v') = M(w)$ and $w < v'$, we have that $B(w) \subset B(v')$, and thus there exists a back-edge $(x',y') \in B(v')$ such that $y' \in T(v',w]$. But since $y = high(u') = high(v')$, we must have $y' \leq y$. Thus, y is not a proper ancestor of w, and so $(x,y) \notin B(w)$, either. We have arrived at a contradiction, as a consequence of our initial supposition. This shows that there is no vertex v' with $M(v') = M(v)$ and $w < v' < v$, such that there exists a $u' \in stackU[v']$ with $low(u') < w$. Thus, $w \leq min\{low(u') \mid \exists v' \text{ with } M(v') = M(v),\ w < v' < v \text{ and } u' \in stackU[v']\}$. Now, by Lemma 3.22, w is the greatest vertex in $M^{-1}(M(v))$ with $w \leq low(u)$. Thus, w must be the greatest vertex in $M^{-1}(M(v))$ that satisfies both $w \leq low(u)$ and $w \leq min\{low(u') \mid \exists v' \text{ with } M(v') = M(v),\ w < v' < v \text{ and } u' \in stackU[v']\}$. ☐

Algorithm 11: Find all 3-cuts $\{(u,p(u)),(v,p(v)),(w,p(w))\}$, where u is a descendant of v, v is a descendant of w with $M(v) = M(w)$, and $w \neq nextM(v)$.

```
1  initialize an array lowestW with n entries
2  foreach vertex v do lowestW[v] ← nextM(v)
3  for v ← 1 to v ← n do
4      while stackU[v].top() ≠ ∅ do
5          u ← stackU[v].pop()
6          w ← lowestW[v]
7          while w > low(u) do w ← lowestW[w]
8          lowestW[v] ← w
9          if b_count(v) = b_count(u) + b_count(w) then
10             mark the triplet {(u,p(u)),(v,p(v)),(w,p(w))}
11         end
12     end
13 end
```

Proposition 3.26. *Algorithm 11 identifies all* 3*-cuts* $\{(u,p(u)),(v,p(v)),(w,p(w))\}$*, where* u *is a descendant of* v*,* v *is a descendant of* w *with* $M(v) = M(w)$*, and* $w \neq nextM(v)$*. Furthermore, it runs in linear time.*

Proof. Let $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ be a 3-cut, where u is a descendant of v, v is a descendant of w with $M(v) = M(w)$, and $w \neq nextM(v)$. By Lemma 3.25, w is the greatest vertex in $M^{-1}(M(v))$ such that $w \leq low(u)$ and $w \leq min\{low(u') \mid \exists v' \text{ with } M(v') = M(v),\ w < v' < v \text{ and } u' \in stackU[v']\}$. By Lemma 3.24, Algorithm 11 will identify w during the processing of u in line 8. As a consequence of proposition 3.12, we have $b\_count(v) = b\_count(u) + b\_count(w)$, and thus the triplet $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ will be marked in line 10. Conversely, let $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ be a triplet that gets marked by Algorithm 11 in line 10. Then, we have $u \in stackU[v]$. Furthermore, Lemma 3.24 implies that w has $M(w) = M(v)$ and $w \leq low(u)$. Then, since $u \in stackU[v]$, we have $low(u) < nextM(v)$, and therefore w is a proper ancestor of v. Now, since $b\_count(v) = b\_count(u) + b\_count(w)$, Lemma 3.22 implies that $\{(u,p(u)),(v,p(v)),(w,p(w))\}$ is a 3-cut. Thus, the correctness of Algorithm 11 is established.

To prove that Algorithm 11 runs in linear time, we will count the number of times that we access the array *lowestW* during the **while** loop in line 7. Specifically, we will show that, by the time the algorithm is terminated, the v entry of $lowestW$, for every vertex v, will have been accessed at most once in line 7. We will prove this inductively, using the inductive proposition: $\Pi(v) \equiv$ after processing v, we have that $\forall v' < v$ $lowestW[v']$ has been accessed at most once in line 7 during the course of the algorithm so far **and** $\forall v' \leq v$ we have that every $w \in T(v', lowestW[v'])$ has $lowestW[w] \geq lowestW[v']$. Thus, (the first part of) $\Pi(n)$ implies the linearity of Algorithm 11. Now, suppose that $\Pi(v-1)$ is true for a $v \in \{1, \ldots, n\}$ (observe that $\Pi(0)$ is trivially true). We will prove that $\Pi(v)$ is also true. Thus we have to show that: after we have processed every $u \in stackU[v]$, we have that $\forall v' < v$ $lowestW[v']$ has been accessed at most once in line 7 during the course of the algorithm so far **and** $\forall v' \leq v$ we have that every $w \in T(v', lowestW[v'])$ has $lowestW[w] \geq lowestW[v']$ (1). Now, suppose that this was a case for a specific $\tilde{u} \in stackU[v]$. We will show that it is still true for the successor u of $\tilde{u}$ in $stackU[v]$. (Of course, due to the inductive hypothesis, (1) is definitely true before we have began processing the elements of $stackU[v]$, and therefore we may also have that u is the first element of $stackU[v]$ in what follows.) Let $\tilde{w}$ be the value of $lowestW[v]$ after the assignment in line 8, during the processing of u. Thus, all vertices that we traversed during the execution of the **while** loop, during the processing of u, are contained in $T[v, \tilde{w}]$. Now let $v' < v$ be a vertex with the property that $lowestW[v']$ has been accessed once in line 7 during the course of the algorithm before the processing of u, and let $\tilde{v}$ be the vertex during whose processing we had to access $lowestW[v']$ in the **while** loop. We will show that $lowestW[v']$ will not be accessed in line 7 during the processing of u. Of course, we may assume that v' is in $T[v, \tilde{w})$, for otherwise it is clear that the v' entry of $lowestW$ will not be accessed during the execution of the **while** loop (since the traversal in **while** loop will not reach vertices lower than $\tilde{w}$, and when it reaches $\tilde{w}$ it will terminate). We note that, since the v' entry of $lowestW$ was accessed during the execution of the **while** loop during the processing of $\tilde{v}$, we have that $lowestW[\tilde{v}]$ is an ancestor of $lowestW[v']$, and therefore a proper ancestor of v'. Now, if $\tilde{v} = v$, then $lowestW[v]$ was assigned $lowestW[\tilde{v}]$, in line 8, during the processing of a predecessor of u in $stackU[v]$. Thus, when we begin processing u, w is assigned a proper ancestor of v' in line 6, before entering the **while** loop, and so the v' entry of $lowestW$ will not be accessed during the execution of the **while** loop. So let's assume that $\tilde{v} < v$. Initially, the variable w is assigned $lowestW[v]$ in line 6. We claim that $lowestW[v]$ is either a descendant of $\tilde{v}$ or a proper ancestor of v'. To see this, suppose, for the sake of contradiction, that $lowestW[v]$ is in $T(\tilde{v}, v']$. Then, we have $\tilde{v} \in T(v, lowestW[v])$, and therefore, since (1) is true for $\tilde{u}$ (the predecessor of u in $stackU[v]$), we have that $lowestW[\tilde{v}] \geq lowestW[v]$. Since $lowestW[\tilde{v}]$ is a proper ancestor of v', this implies that $v' > lowestW[v]$, contradicting the supposition $lowestW[v] \leq v'$. Thus, before executing the **while** loop, we have that w is either a descendant of $\tilde{v}$ or a proper ancestor of v'. Now suppose that the **while** loop has been executed 0 or more times, and w is assigned a descendant of $\tilde{v}$ or a proper ancestor of v'. We will show that if we execute the **while** loop once more, w will either be assigned a descendant of $\tilde{v}$ or a proper ancestor of v'. Of course, if w is a proper ancestor of v', the same is true for $lowestW[w]$. Moreover, if $w = \tilde{v}$, then, as noted above, we have that $lowestW[w]$ is a proper ancestor of v'. So let's assume that w is a proper descendant of $\tilde{v}$, and suppose, for the sake of contradiction, that $lowestW[w]$ is in $T(\tilde{v}, v']$. Then, since $\tilde{v} \in T(w, lowest[w])$, due to the inductive hypothesis we have that $lowestW[\tilde{v}] \geq lowestW[w]$. Since we also have $v' > lowestW[\tilde{v}]$, this contradicts the supposition $lowestW[w] \geq v'$. Thus, if w is a proper descendant of $\tilde{v}$, $lowestW[w]$ is either a descendant of $\tilde{v}$ or a proper ancestor of v'. In any case, then, during the execution of the **while** loop, w will be assigned either a descendant of $\tilde{v}$ or a proper ancestor of v', and thus the v' entry of $lowestW$ will not be accessed.

It remains to show that, after the processing of u, for every $w \in T(v, \tilde{w})$ we have $lowestW[w] \geq \tilde{w}$. Due to the inductive hypothesis, this is definitely true for every $w \in T(v, lowestW[v])$ (where $lowestW[v]$ here has the value after the processing of $\tilde{u}$ and before the processing of u), since

$lowestW[v] \geq \tilde{w}$, and every such w has $lowestW[w] \geq lowestW[v]$. Now let's assume that $w \in T[lowestW[v], \tilde{w})$, and suppose, for the sake of contradiction, that $lowestW[w] < \tilde{w}$. Then it cannot be that case that $w = lowestW[v]$, since $\tilde{w} \leq lowestW[lowestW[v]]$ (for the existence of a $w \in T[lowestW[v], \tilde{w})$ implies that $\tilde{w} \neq lowestW[v]$). Now, since $lowestW[v] > w > \tilde{w}$, there must exist a w' such that $w' \in T[lowestW[v], w]$, $lowestW[w'] < w$ and $lowestW[w'] \geq \tilde{w}$. Since $lowestW[w] < \tilde{w}$, we cannot $w' = w$. Then, $w \in T(w', lowestW[w'])$, and thus, due to the inductive hypothesis, we have $lowestW[w] \geq lowestW[w']$. Since $lowestW[w'] \geq \tilde{w}$, this implies that $lowestW[w] \geq \tilde{w}$, contradicting the supposition $lowestW[w] < \tilde{w}$. Thus, every $w \in T(v, \tilde{w})$ has $lowestW[w] \geq \tilde{w}$. The proof that (1) is true for u is complete. Due to the generality of $u \in stackU[v]$, this implies that $\Pi(v)$ is true. This shows, by induction, that $\Pi(n)$ is true, and the linearity of Algorithm 11 is thus established. □

4 Computing the 4-edge-connected components in linear time

Now we consider how to compute the 4-edge-connected components of an undirected graph G in linear time. First, we reduce this problem to the computation of the 4-edge-connected components of a collection of auxiliary 3-edge-connected graphs.

4.1 Reduction to the 3-edge-connected case

Given a (general) undirected graph G, we execute the following steps:

- Compute the connected components of G.
- For each connected component, we compute the 2-edge-connected components which are subgraphs of G.
- For each 2-edge-connected component, we compute its 3-edge-connected components $C_1, \ldots, C_\ell$.
- For each 3-edge-connected component C_i, we compute a 3-edge-connected auxiliary graph H_i, such that for any two vertices x and y, we have $x \overset{G}{\equiv}_4 y$ if and only if x and y are both in the same auxiliary graph H_i and $x \overset{H_i}{\equiv}_4 y$.
- Finally, we compute the 4-edge-connected components of each H_i.

Steps 1–3 take overall linear time [19, 22]. We describe step 5 in the next section, so it remains to give the details of step 4. Let H be a 2-edge-connected component (subgraph) of G. We can construct a compact representation of the 2-cuts of H, which allows us to compute its 3-edge-connected components $C_1, \ldots, C_\ell$ in linear time [6, 22]. Now, since the collection $\{C_1, \ldots, C_\ell\}$ constitutes a partition of the vertex set of H, we can form the quotient graph Q of H by shrinking each C_i into a single node. Graph Q has the structure of a tree of cycles [2]; in other words, Q is connected and every edge of Q belongs to a unique cycle. Let (C_i, C_j) and (C_i, C_k) be two edges of Q which belong to the same cycle. Then (C_i, C_j) and (C_i, C_k) correspond to two edges (x, y) and (x', y') of G, with $x, x' \in C_i$. If $x \neq x'$, we add a virtual edge (x, x') to $G[C_i]$. (The idea is to attach (x, x') to $G[C_i]$ as a substitute for the cycle of Q which contains (C_i, C_j) and (C_i, C_k).) Now let $\bar{C}_i$ be the graph $G[C_i]$ plus all those virtual edges. Then $\bar{C}_i$ is 3-edge-connected and its 4-edge-connected components are precisely those of G that are contained in C_i [2]. Thus we can compute the 4-edge-connected components of G by computing the 4-edge-connected components of the graphs $\bar{C}_1, \ldots, \bar{C}_\ell$ (which can easily be constructed in total linear time). Since every $\bar{C}_i$ is 3-edge-connected, we can apply Algorithm 12 of the following section to compute its 4-edge-connected components in linear time. Finally, we define the multiplicity $m(e)$ of an edge $e \in \bar{C}_i$ as follows: if e is virtual, $m(e)$ is the number of edges of the cycle of Q which corresponds to e; otherwise, $m(e)$ is 1. Then, the number of minimal 3-cuts of H is given by the sum of all $m(e_1) \cdot m(e_2) \cdot m(e_3)$, for every 3-cut $\{e_1, e_2, e_3\}$ of $\bar{C}_i$, for every $i \in \{1, \ldots, l\}$ [2]. Since the 3-cuts of every $\bar{C}_i$ can be computed in linear time, the minimal 3-cuts of H can also be computed within the same time bound.

4.2 Computing the 4-edge-connected components of a 3-edge-connected graph

Now we describe how to compute the 4-edge-connected components of a 3-edge-connected graph G in linear time. Let r be a distinguished vertex of G, and let C be a minimum cut of G. By removing C from G, G becomes disconnected into two connected components. We let V_C denote the connected component of $G \setminus C$ that does not contain r, and we refer to the number of vertices of V_C as the *r-size* of the cut C. (Of course, these notions are relative to r.)

Let $G = (V, E)$ be a 3-edge-connected graph, and let $\mathcal{C}$ be the collection of the 3-cuts of G. If the collection $\mathcal{C}$ is empty, then G is 4-edge-connected, and V is the only 4-edge-connected component of G. Otherwise, let $C \in \mathcal{C}$ be a 3-cut of G. By removing C from G, G is separated into two connected components, and every 4-edge-connected component of G lies entirely within a connected component of $G \setminus C$. This observation suggests a recursive algorithm for computing the 4-edge-connected components of G, by successively splitting G into smaller graphs according to its 3-cuts. Thus, we start with a 3-cut C of G, and we perform the splitting operation shown in Figure 8. Then we take another 3-cut C' of G and we perform the same splitting operation on the part which contains (the corresponding 3-cut of) C'. We repeat this process until we have considered every 3-cut of G. When no more splits are possible, the connected components of the final split graph correspond (by ignoring the newly introduced vertices) to the 4-edge-connected components of G.

To implement this procedure in linear time, we must take care of two things. First, whenever we consider a 3-cut C of G, we have to be able to know which ends of the edges of C belong to the same connected component of $G \setminus C$. And second, since an edge e of a 3-cut of the original graph may correspond to two virtual edges of the split graph, we have to be able to know which is the virtual edge that corresponds to e. We tackle both these problems by locating the 3-cuts of G on a DFS-tree T of G rooted at r, and by processing them in increasing order with respect to their r-size. By locating a 3-cut $C \in \mathcal{C}$ on T we can answer in $O(1)$ time which ends of the edges of C belong to the same connected component of $G \setminus C$. And then, by processing the 3-cuts of G in increasing order with respect to their size, we ensure that (the 3-cut that corresponds to) a 3-cut $C \in \mathcal{C}$ that we process lies in the split part of G that contains r.

Now, due to the analysis of the preceding sections, we can distinguish the following types of 3-cuts on a DFS-tree T (see also Figure 1):

- (I) $\{(v, p(v)), (x_1, y_1), (x_2, y_2)\}$, where (x_1, y_1) and (x_2, y_2) are back-edges.
- (IIa) $\{(u, p(u)), (v, p(v)), (x, y)\}$, where u is a descendant of v and $(x, y) \in B(v)$.
- (IIb) $\{(u, p(u)), (v, p(v)), (x, y)\}$, where u is a descendant of v and $(x, y) \in B(u)$.
- (III) $\{(u, p(u)), (v, p(v)), (w, p(w))\}$, where w is an ancestor of both u and v, but u, v are not related as ancestor and descendant.
- (IV) $\{(u, p(u)), (v, p(v)), (w, p(w))\}$, where u is a descendant of v and v is a descendant of w.

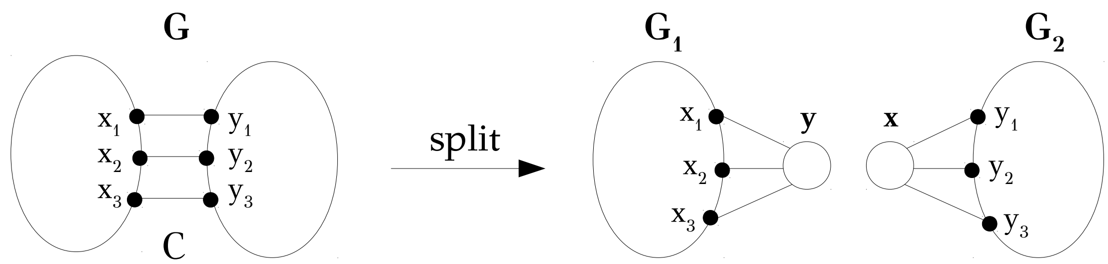

Figure 8: $C = \{(x_1, y_1), (x_2, y_2), (x_3, y_3)\}$ is a 3-cut of G, with $\{x_1, x_2, x_3\}$ and $\{y_1, y_2, y_3\}$ lying in different connected components of $G \setminus C$. The split operation of G at C consists of the removal the edges of C from G, and the introduction of two new nodes x, y, and six virtual edges $(x_1, y), (x_2, y), (x_3, y), (x, y_1), (x, y_2), (x, y_3)$. Now, the split graph is made of two connected components, G_1 and G_2. Every 3-cut $C' \neq C$ of G (or more precisely: a 3-cut that corresponds to C') lies entirely within G_1 or G_2. Conversely, every 3-cut of either G_1 or G_2 corresponds to a 3-cut of G. Thus, every 4-edge-connected component of G lies entirely within G_1 or G_2.

Let r be the root of T. Then, for every 3-cut $C \in \mathcal{C}$, V_C is either $T(v)$, or $T(v) \setminus T(u)$, or $T(w) \setminus (T(u) \cup T(v))$, or $T(u) \cup (T(w) \setminus T(v))$, depending on whether C is of type (I), (II), (III), or (IV), respectively. Thus we can immediately calculate the size of C and the ends of its edges that lie in V_C. In particular, the size of C is either $ND(v)$, or $ND(v) - ND(u)$, or $ND(w) - ND(u) - ND(v)$, or $ND(u) + ND(w) - ND(v)$, depending on whether it is of type (I), (II), (III), or (IV), respectively; V_C contains either $\{v, x_1, x_2\}$, or $\{p(u), v, x\}$, or $\{p(u), v, y\}$, or $\{p(u), p(v), w\}$, or $\{u, p(v), w\}$, depending on whether C is of type (I), (IIa), (IIb), (III), or (IV), respectively.

Algorithm 12 shows how we can compute the 4-edge-connected components of G in linear time, by repeatedly splitting G into smaller graphs according to its 3-cuts. When we process a 3-cut C of G, we have to find the edges of the split graph that correspond to those of C, in order to delete them and replace them with (new) virtual edges. That is why we use the symbol v', for a vertex $v \in V$, to denote a vertex that corresponds to v in the split graph. (Initially, we set $v' \leftarrow v$.) Now, if (x, y) is an edge of C with $x \in V_C$, the edge of the split graph corresponding to (x, y) is (x', y'). Then we add two new vertices v_C and $\tilde{v_C}$ to G, and the virtual edges $(x', \tilde{v_C})$ and (v_C, y'). Finally, we let x correspond to v_C, and so we set $x' \leftarrow v_C$. This is sufficient, since we process the 3-cuts of G in increasing order with respect to their size, and so the next time we meet the edge (x, y) in a 3-cut, we can be certain that it corresponds to (v_C, y').

Algorithm 12: Compute the 4-edge-connected components of a 3-edge-connected graph $G = (V, E)$

Find the collection $\mathcal{C}$ of the 3-cuts of G
Locate and classify the 3-cuts of G on a DFS-tree of G rooted at r
For every $C \in \mathcal{C}$, calculate $size(C)$ (relative to r)
Sort $\mathcal{C}$ in increasing order w.r.t. the *size* of its elements
foreach $v \in V$ **do** Set $v' \leftarrow v$
foreach $C = \{(x_1, y_1), (x_2, y_2), (x_3, y_3)\} \in \mathcal{C}$ **do**
    Find the ends of the edges of C that lie in V_C *// Let those ends be x_1,x_2 and x_3*
    Remove the edges (x'_1, y'_1),(x'_2, y'_2),(x'_3, y'_3) from G
    Introduce two new vertices v_C and $\tilde{v_C}$ to G
    Add the edges $(x'_1, \tilde{v_C})$,$(x'_2, \tilde{v_C})$,$(x'_3, \tilde{v_C})$,(v_C, y'_1),(v_C, y'_2),(v_C, y'_3) to G
    Set $x'_1 \leftarrow v_C$, $x'_2 \leftarrow v_C$, $x'_3 \leftarrow v_C$
end
Output the connected components of G, ignoring the newly introduced vertices

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