

Stochastic U-Curve Branch and Bound

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1 Input Generation

To generate the input for the problem we created two functions. The first creates a vector of floating points that simulates the values of a chain of a boolean lattice that respects the U-Curve assumption; and the second one adds a random noise to the values of the vector.

1.1 Chain Generation

The chain is generated based on a polynomial of second degree with positive leading coefficient. This polynomial has the minimum value of 0.1 evaluated at some point $x^* \in [0, 1]$ which is determined by the user. The algorithm receives two arguments: the first one, n , represents the size of the chain; and the second one, $center \in [0, 1]$, specifies where is the minimum of the polynom. After creating a random polynomial that holds our constraints, we split the $[0, 1]$ interval in n equally spaced points, and evaluate the polynomial at these points, generating the curve.

1.2 Noise

The noise is applied to the vector created by *GeneratePoints*, by adding that is in the interval $[-\alpha \frac{curve_amplitude}{n}, \alpha \frac{curve_amplitude}{n}]$, where $curve_amplitude = max(v) - min(v)$ and α is a random variable with gaussian distribution with mean 0 and standard deviation σ .

Algorithm 1 U-Curve Input Creator

```
1: procedure GENERATEPOINTS( $n, max\_distance, center$ )  
2:    $points \leftarrow \{0, \dots, 0\}$   
3:    $p.a \leftarrow random()$   
4:    $p.b \leftarrow -2 * p.a * center$   
5:    $p.c = (p.a^2 - 0.1)/(4 * p.a)$   
6:    $dx \leftarrow 1/n$   
7:    $x \leftarrow 0$   
8:   for  $i \in \{0, \dots, n\}$  do  
9:      $points_i \leftarrow p(x)$   
10:     $x \leftarrow x + dx$   
11:  end for  
12:   $j \leftarrow n * random()$   
13:   $plain\_size \leftarrow (n - j) * random()$   
14:  for  $k \in \{1, \dots, plain\_size\}$  do ▷ Creates a plain area in the chain  
15:     $points[j + k] \leftarrow points[j]$   
16:  end for  
17:  return  $points$   
18: end procedure
```

Figure 1: Example of a curve generated with $\sigma = 0$

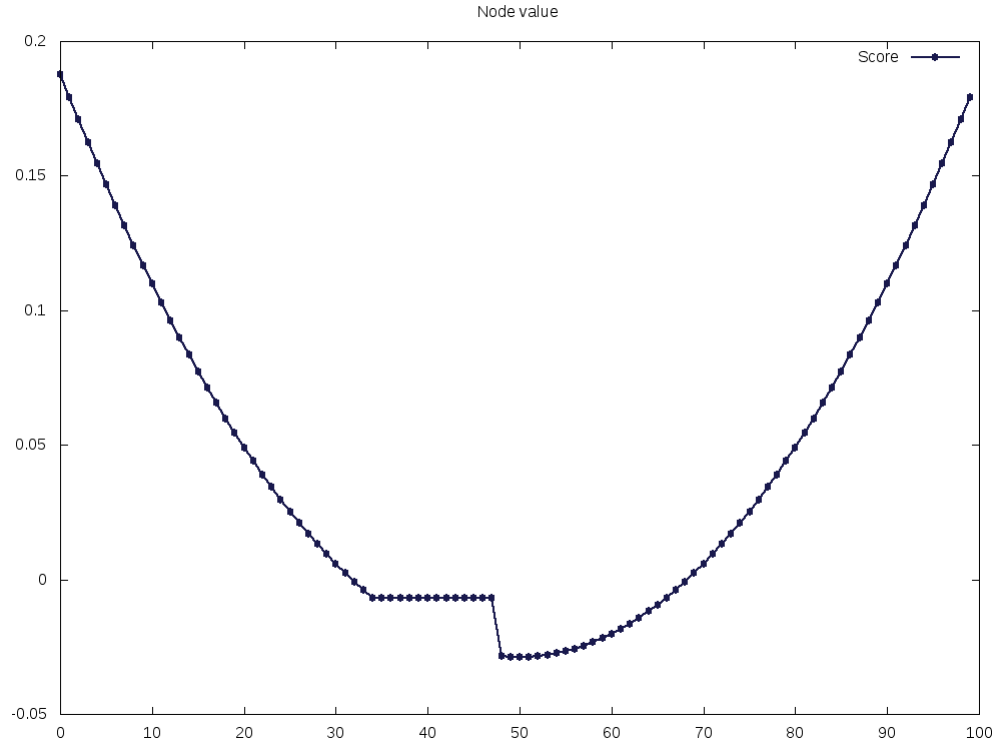


Figure 2: Example of a curve generated with $\sigma = 1$

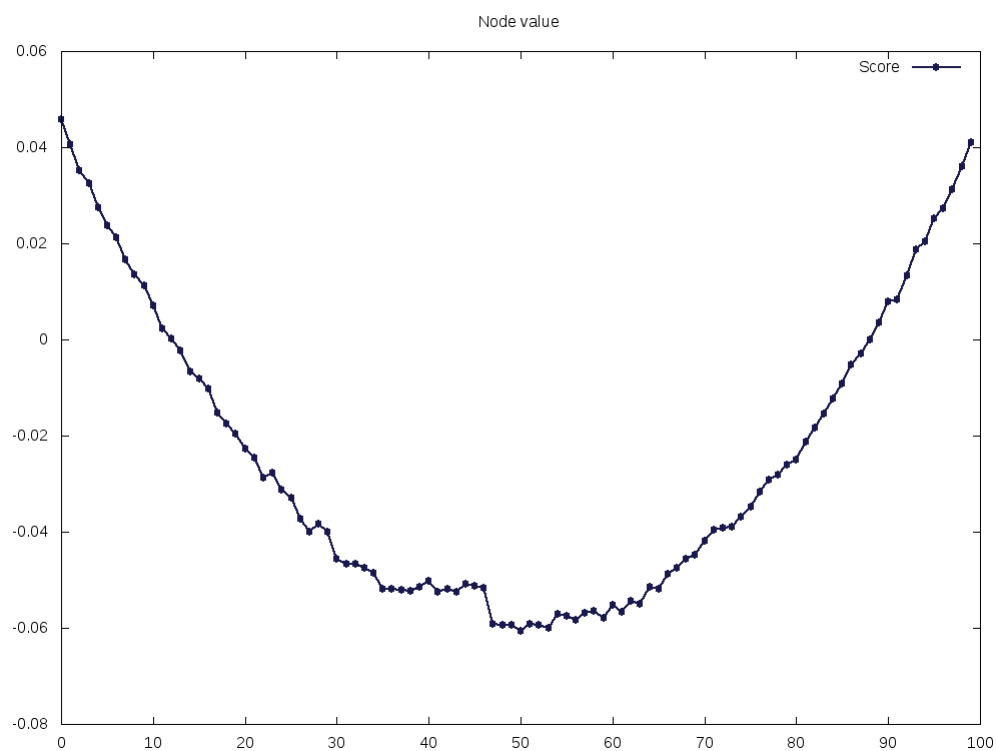
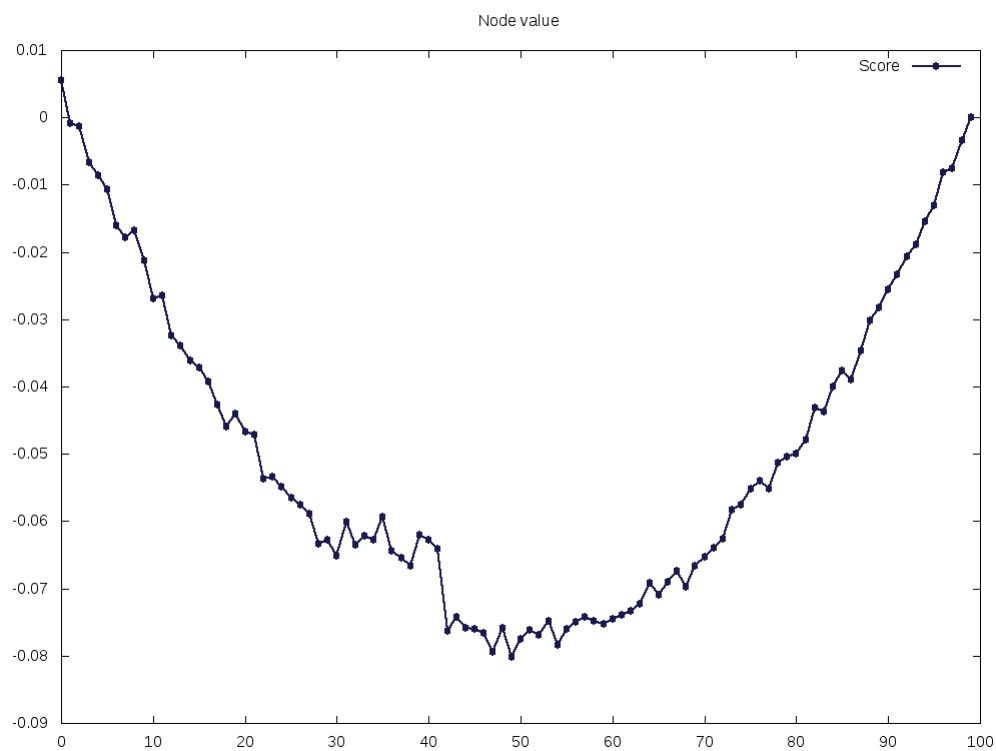


Figure 3: Example of a curve generated with $\sigma = 2$



2 Bisection Algorithms

2.1 Traditional Bisection

This is the simplest bisection algorithm we implemented. The basic idea of this algorithm is to divide the original problem in two halves and, by analysing the neighbours of the node in the middle, determine which half has the minimum and then solve this half recursively. To guarantee the optimality of the algorithm (when the input respects the U-Curve assumption) we solve both halves when the neighbours can't determine if the minimum lies to the left or right of the middle point.

Algorithm 2

```
1: procedure BISECTION( $v$ )
2:    $n \leftarrow v.length$ 
3:    $i \leftarrow n/2$ 
4:   if ( $valley(v, i)$ ) then
5:     return  $v[i]$ 
6:   else
7:      $direction \leftarrow SelectSide(v, i)$ 
8:     if  $direction = Left$  then
9:       return  $Bisection([v_i, \dots, v_n])$ 
10:    else if  $direction = Right$  then
11:      return  $Bisection([v_0, \dots, v_{i-1}])$ 
12:    else ▷ Unknown direction
13:      return  $min(Bisection([v_0, \dots, v_{i-1}]), Bisection([v_i, \dots, v_n]))$ 
14:    end if
15:  end if
16: end procedure
```

Algorithm 3

```
1: procedure SELECTSIDE( $v, i$ )
2:    $d = v[i + 1] - v[i - 1]$ 
3:   if  $|d| < \epsilon$  then
4:     return Unknown
5:   else if  $d > 0$  then
6:     return Left
7:   else
8:     return Right
9:   end if
10: end procedure
```

2.2 Mid-neighbour Bisection

As an attempt to minimize the effects of noise in the traditional bisection algorithm we developed the Mid-neighbour Bisection, which brings two new ideas to the traditional bisection, that changes the evaluated points and also how we divide the problem in smaller problems.

The first idea consists in changing the points that are evaluated to decide which side to go. Instead of looking to the neighbours of the middle point, we now evaluate the points that are in the middle of the left half and right half. After evaluating these points, we calculate the difference between the left-middle point and middle point and also the difference between the right-middle point and the middle point to get two abstract slopes that can guarantee us which fraction of the input has the minimum value.

The second idea considers the "reliability" of the abstract slopes mentioned before, for instance, if we say that the left slope (middle point - left-middle point) is negative, it's more likely that the function is going to increase from the left-middle point and before if the distance between these two points is greater. That happens because if the function decreases from the left-middle point and before, then the left-middle point suffered some noise that caused a peak (an inverted u-shape) and, considering that the points should describe a u-shape that would imply in a bigger noise for bigger distances of middle point and left-middle point. We modeled the "reliability" of the abstract slope as a linear function that decreases from one to zero in $\lg n$ steps.

The abstract slopes are reduced to three different cases: 1 for growing, -1 for decreasing and 0 for plain areas or unreliable difference. Since we have three different slopes, there are nine different cases that need to be handled by the algorithm. Suppose that we are using the mid-neighbour bisection on a vector $v = \{v_1, \dots, v_n\}$ and the right-middle, middle and left-middle point are, respectively, lm , m , and rm . Then, the following pictures represent how the algorithm finds the minimum recursively.

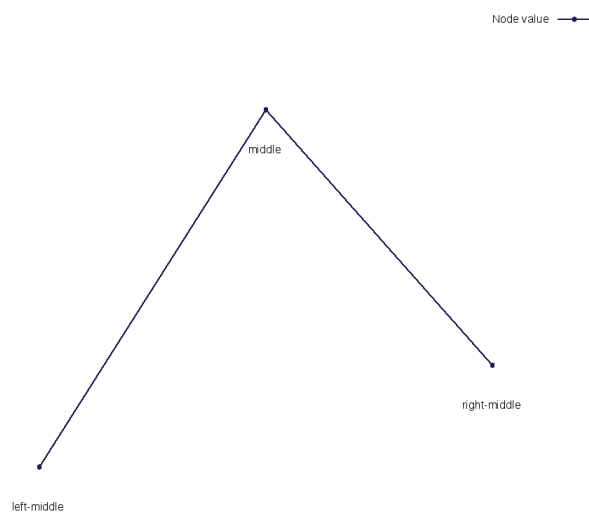


Figure 4: In this case we split the original problem into the two problem of finding the minimum of $\{v_1, \dots, v_{m-1}\}$ and $\{v_m, \dots, v_n\}$.

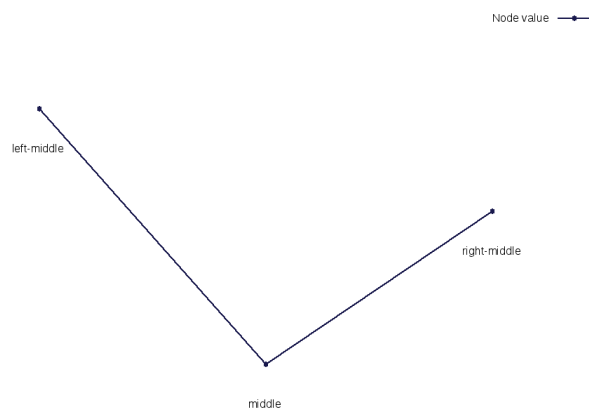


Figure 5: In this case we reduce the problem to finding the minimum of $\{v_{lm}, \dots, v_{rm}\}$.

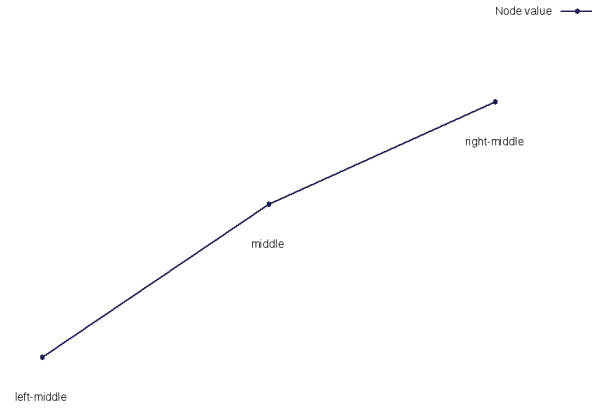


Figure 6: For this case we reduce the problem to finding the minimum of $\{v_1, \dots, v_m\}$.

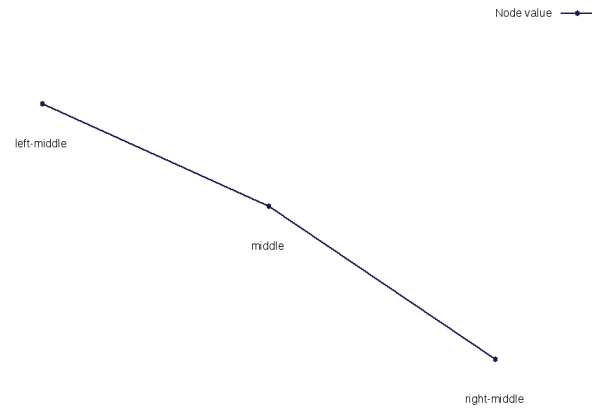


Figure 7: In this case we reduce the problem to finding the minimum of $\{v_m, \dots, v_n\}$.

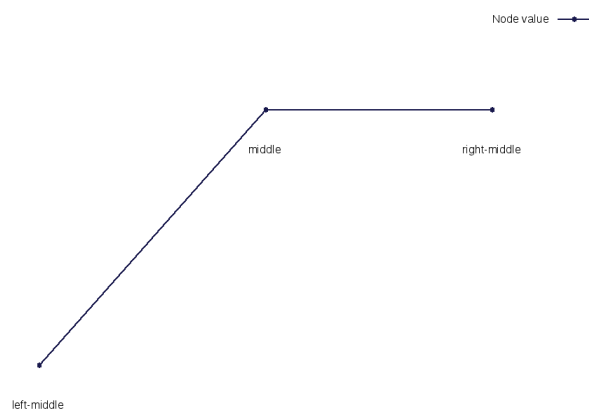


Figure 8: For this case we reduce the problem to finding the minimum of $\{v_1, \dots, v_m\}$.

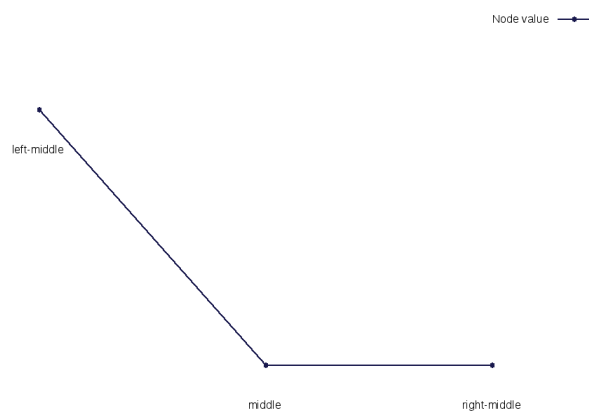


Figure 9: For this case we reduce the problem to finding the minimum of $\{v_{lm}, \dots, v_m\}$.

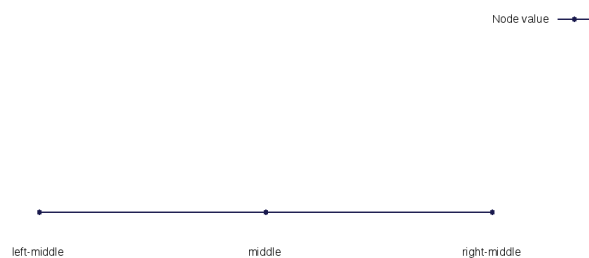


Figure 10: In this case we split the original problem into the two problem of finding the minimum of $\{v_1, \dots, v_{m-1}\}$ and $\{v_m, \dots, v_n\}$.

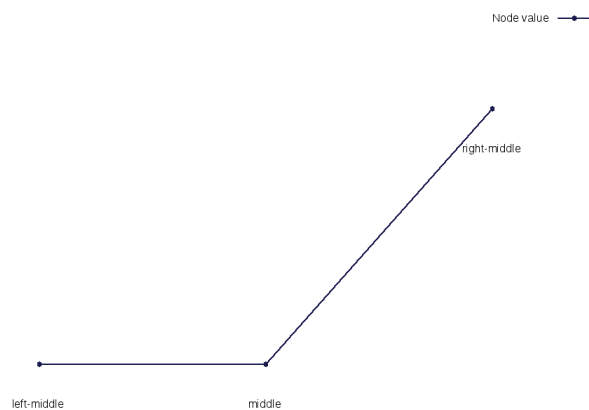


Figure 11: In this case we reduce the problem to finding the minimum of $\{v_1, \dots, v_m\}$.

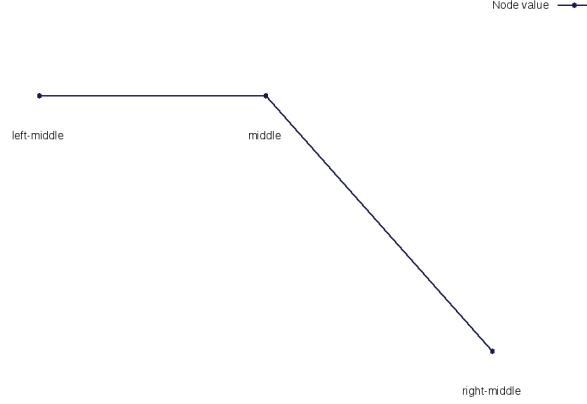


Figure 12: In this case we reduce the original problem to finding the minimum of $\{v_m, \dots, v_n\}$

2.3 U-Curve Probabilistic Bisection

The U-Curve Probabilistic Bisection (UPB) is a stochastic version of the algorithm we called "Traditional Bisection". The UPB algorithm keeps a probability mass function $f_i(x)$, for every iteration i and every node x of the search space, that can represent the algorithm belief, on iteration i , that the node x is the answer to the problem. This algorithm has two key points: selecting the node to be evaluated and updating the probability mass function.

Different from the Traditional Bisection, we don't select the element that is the middle of the input to evaluate, instead we select the m -th element of the input vector v such that:

$$m = \min_{1 \leq i \leq n} \{i \mid f(v_i) \geq \frac{1}{2}\}.$$

, i.e the median of the possible solutions. The algorithm then compares the adjacent nodes of v_m and decides which side the solution should be the same way it was done in the traditional bisection.

We call p_c the probability that we chose the correct side when evaluating v_m 's neighbours and $\alpha = \sum_{j=1}^m f_i(v_j)$. In the case where the actual solution lies in the right side of v_m , the

probability mass function update is calculated by:

$$f_{i+1}(y) = \begin{cases} (\frac{1}{1-\alpha})p_c f_i(y) & \text{if } y \geq v_m \\ \alpha(1 - p_c)f_i(y) & \text{if } y < v_m \end{cases}$$

. This update is similar for the case when the solution lies in the left side of v_m . If there is no defined value for f_0 , we simply assume that the probability of being a solution is distributed uniformly between all nodes of the chain.

The algorithm terminates when the first quantile or when the third quantile, of the possible solutions, are the same node as the second quantile (median), which is the solution given by the algorithm. This termination condition avoids an early termination, that would be caused by a local minimal element if we used the same termination condition as we did in the traditional bisection.

Algorithm 4

```

1: procedure UPB( $v, pmf$ )
2:    $n \leftarrow v.length$ 
3:    $Quantiles \leftarrow FindQuantiles(pmf)$ 
4:   while  $Quantiles_1 \neq Quantiles_2$  and  $Quantiles_2 \neq Quantiles_3$  do
5:      $direction \leftarrow SelectSide(v, i)$ 
6:     if direction is Unknown then ▷ Unknown direction
7:       return  $SplitUPB(v, pmf, Quantile_2)$ 
8:     else
9:        $UpdatePMF(pmf, Quantile_2, F(Quantile_2), direction)$ 
10:    end if
11:     $Quantiles \leftarrow FindQuantiles(pmf)$ 
12:  end while
13:  return  $Quantile_2$ 
14: end procedure

```

2.4 Mid-neighbour Probabilistic Bisection

The Mid-neighbour Probabilistic Bisection (MPB) is a probabilistic algorithm that partitions the search space into four different parts and, according to the value of the points between the subsets, decides in which portion of the chain the minimum should be. The partition on the chain is made according to the quantiles of the pmf and the points we evaluate

are v_{lm} , v_m and v_{rm} , which we define as:

- $lm = \min_{1 \leq i \leq n} \{i \mid f(v_i) \geq \frac{1}{4}\}.$
- $m = \min_{1 \leq i \leq n} \{i \mid f(v_i) \geq \frac{2}{4}\}.$
- $rm = \min_{1 \leq i \leq n} \{i \mid f(v_i) \geq \frac{3}{4}\}.$

After finding the points v_{lm} , v_m and v_{rm} we calculate the cost c of these points and update the pmf according to the following rules:

- If $c(v_{rm}) - c(v_{lm}) > \epsilon$: then we guess that the minimum should be to the left of v_{rm} .
- If $c(v_{rm}) - c(v_{lm}) < -\epsilon$: then we guess that the minimum should be to the right of v_{lm} .
- If $|c(v_{rm}) - c(v_{lm})| < \epsilon$ and $v_m < \min(v_{rm}, v_{lm})$: then we guess that the minimum should be between v_{lm} and v_{rm}
- If $|c(v_{rm}) - c(v_{lm})| < \epsilon$ and $v_m \geq \min(v_{rm}, v_{lm})$: then we can't guess where the minimum is. To overcome this, we divide the problem in the node v_m so we can solve, recursively, two problems and return the minimum of the two solutions.

Algorithm 5

```
1: procedure MPB( $v, pmf$ )
2:    $n \leftarrow v.length$ 
3:    $Quantiles \leftarrow FindQuantiles(pmf)$ 
4:    $v_{lm} \leftarrow Quatiles_1$ 
5:    $v_m \leftarrow Quatiles_2$ 
6:    $v_{rm} \leftarrow Quatiles_3$ 
7:   while  $v_{lm} \neq v_m$  and  $v_{rm} \neq v_m$  do
8:      $d \leftarrow c(v_{rm}) - c(v_{lm})$ 
9:     if  $abs(d) < \epsilon$  then
10:      if  $v_m < \min(v_{rm}, v_{lm})$  then
11:         $UpdatePMF(pmf, v_{lm}, F(v_{lm}), Right)$ 
12:         $UpdatePMF(pmf, v_{rm}, F(v_{lm}), Left)$ 
13:      else ▷ Unknown direction
14:        return  $SplitMPB(v, pmf, v_m)$ 
15:      end if
16:    else if  $d > \epsilon$  then
17:       $UpdatePMF(pmf, v_{rm}, F(v_{rm}), Left)$ 
18:    else
19:       $UpdatePMF(pmf, v_{lm}, F(v_{lm}), Right)$ 
20:    end if
21:     $Quantiles \leftarrow FindQuantiles(pmf)$ 
22:     $v_{lm} \leftarrow Quatiles_1$ 
23:     $v_m \leftarrow Quatiles_2$ 
24:     $v_{rm} \leftarrow Quatiles_3$ 
25:  end while
26:  return  $v_m$ 
27: end procedure
```

3 Results

