

Binary segmentation

Toby Dylan Hocking

Motivation for changepoint detection in time series data

- ▶ Detecting changes/abnormalities important in medicine.

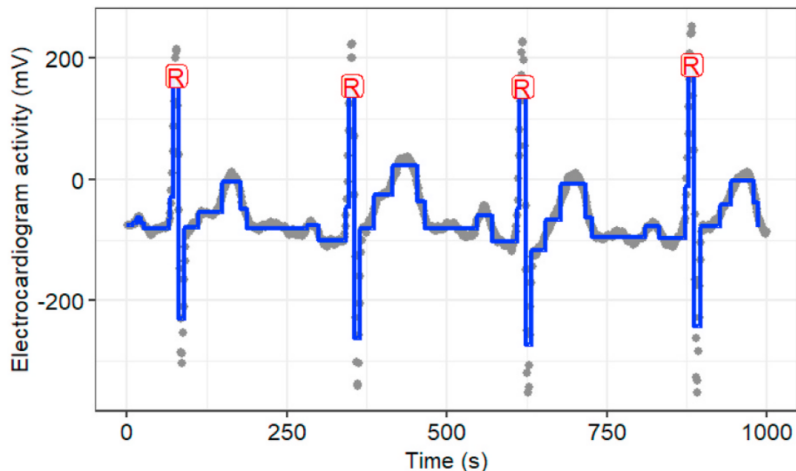


Figure 1: Electrocardiograms (heart monitoring), Fotoohinasab et al, Asilomar conference 2020.

Motivation for changepoint detection in time series data

- ▶ Detecting the time when a spike occurs is important in neuroscience.

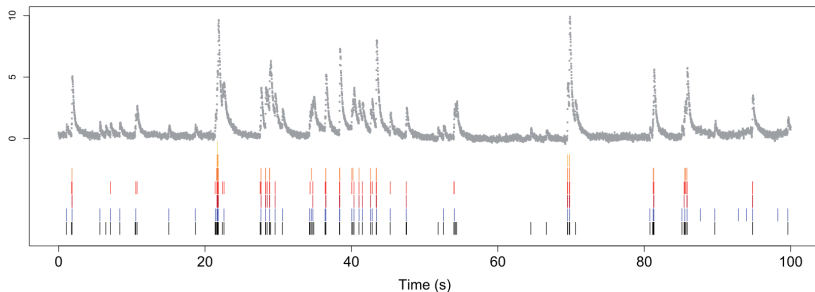


Figure 2: Neural spikes in calcium imaging data, Jewell et al, Biostatistics 2019.

Motivation for changepoint detection in genomic data sequences

- ▶ Detecting breakpoints is important in diagnosis of some types of cancer, such as neuroblastoma.

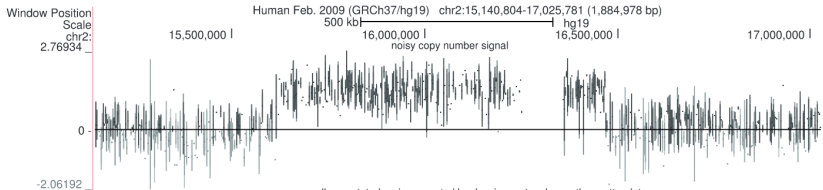


Figure 3: DNA copy number data, breakpoints associated with aggressive cancer, Hocking et al, Bioinformatics 2014.

Motivation for changepoint detection in genomic data sequences

- ▶ Detecting peaks (up/down changes) in genomic data is important in order to understand which genes are active or inactive.

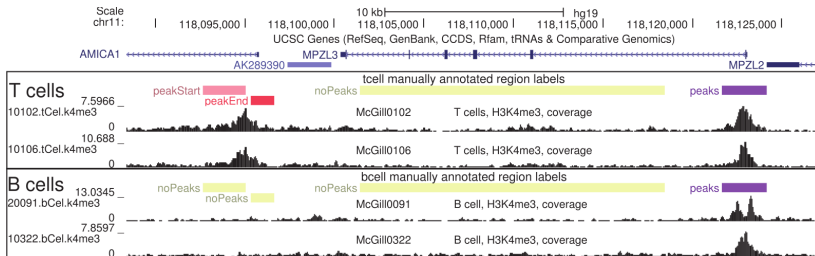


Figure 4: ChIP-seq data for characterizing active regions in the human genome, Hocking et al, Bioinformatics 2017.

Segmentation / changepoint detection framework

- ▶ Let $x_1, \dots, x_n \in \mathbb{R}$ be a data sequence over space or time (logratio column in DNA copy number data below).
- ▶ Where are the abrupt changes in the data sequence?

```
## data.table 1.17.99 EN DEVELOPPEMENT build 2025-04-28 04:00
```

```
## *****
```

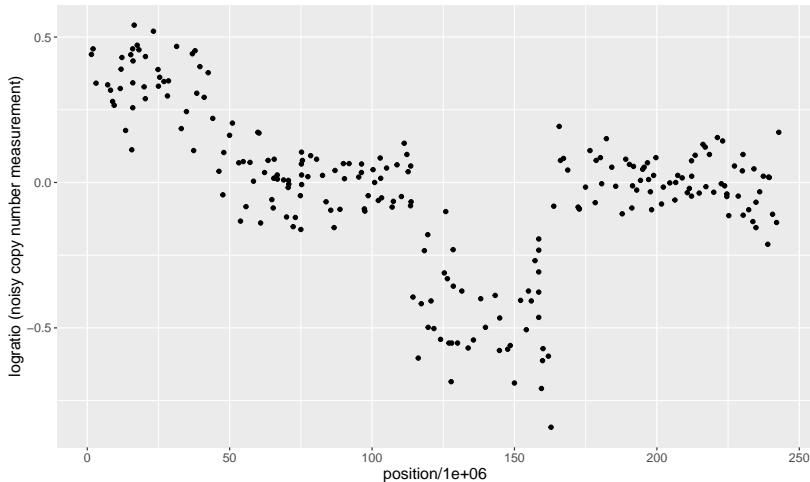
```
## Running data.table in English; package support is available
```

```
## *****
```

	profile.id	chromosome	position	logratio
	<fctr>	<fctr>	<int>	<num>
## 1:	4	2	1472476	0.44042072
## 2:	4	2	2063049	0.45943162
## 3:	4	2	3098882	0.34141652
## 4:	4	2	7177474	0.33571191
## 5:	4	2	8179390	0.31730407
## ---				
## 230:	4	2	239227603	0.01863417
## 231:	4	2	239471307	0.01720929

Segmentation / changepoint data visualization

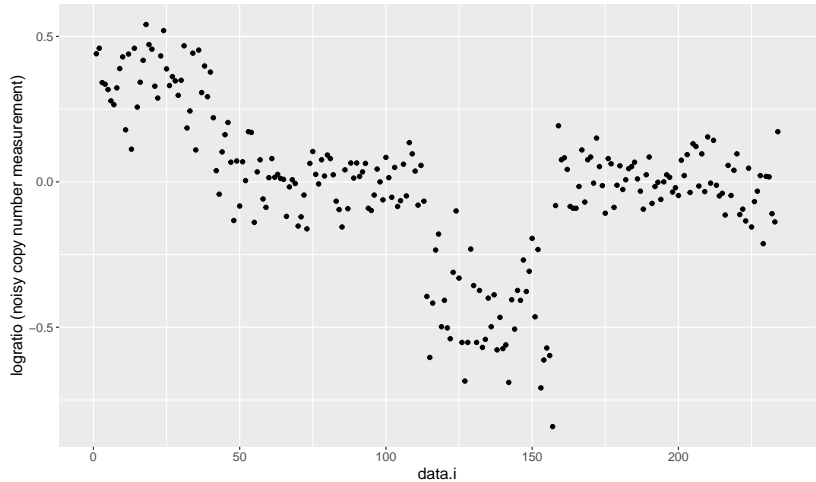
- ▶ Let $x_1, \dots, x_n \in \mathbb{R}$ be a data sequence over space or time.
- ▶ Where are the abrupt changes in the data sequence?



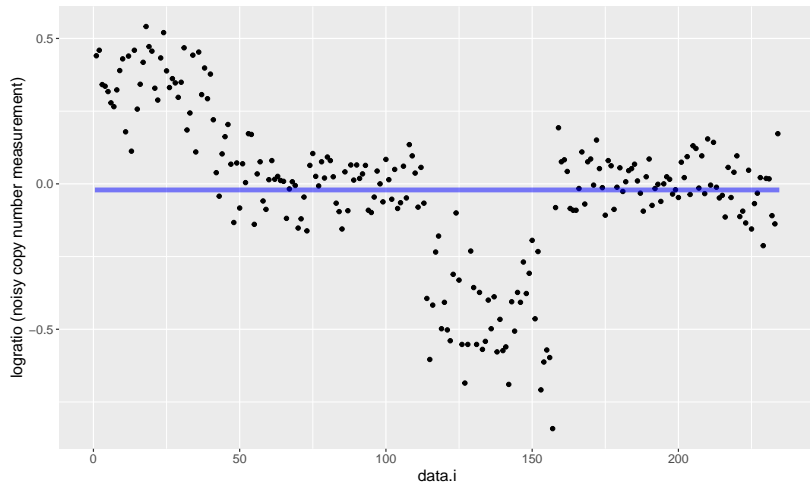
Assume normal distribution with change in mean, constant variance

- ▶ There are a certain number of clusters/segments $K \in \{1, \dots, n\}$.
- ▶ Each segment $k \in \{1, \dots, K\}$ has its own mean parameter $\mu_k \in \mathbb{R}$.
- ▶ There is some constant variance parameter $\sigma^2 > 0$ which is common to all segments.
- ▶ For each data point i on segment $k \in \{1, \dots, K\}$ we have $x_i \sim N(\mu_k, \sigma^2)$ – normal distribution.
- ▶ This normal distribution assumption means that we want to find segments/changepoints with mean m that minimize the square loss, $(x - m)^2$.
- ▶ Other distributional assumptions / loss functions are possible.

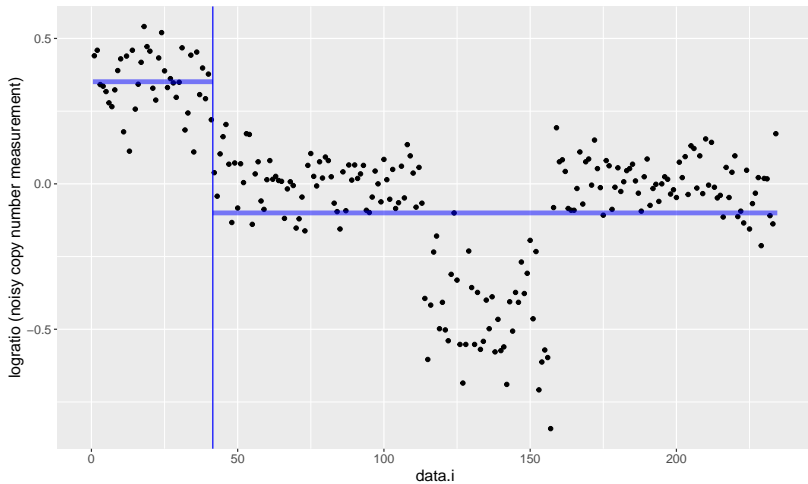
Visualize data sequence



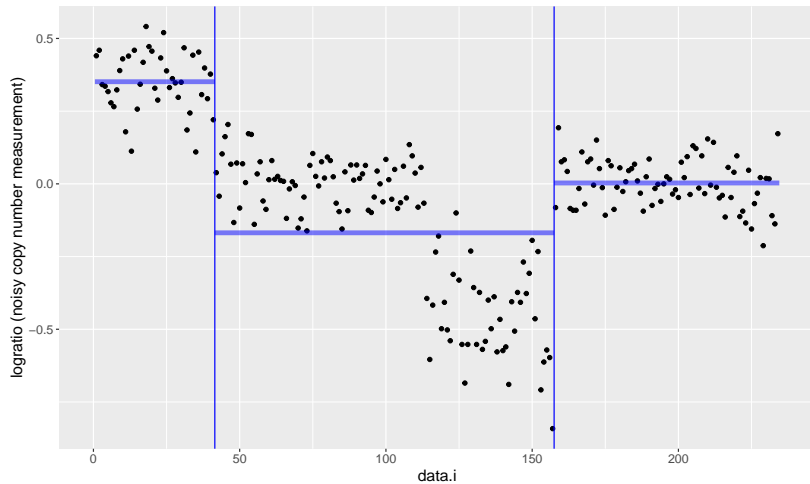
Simplest model, 1 segment, 0 changepoints



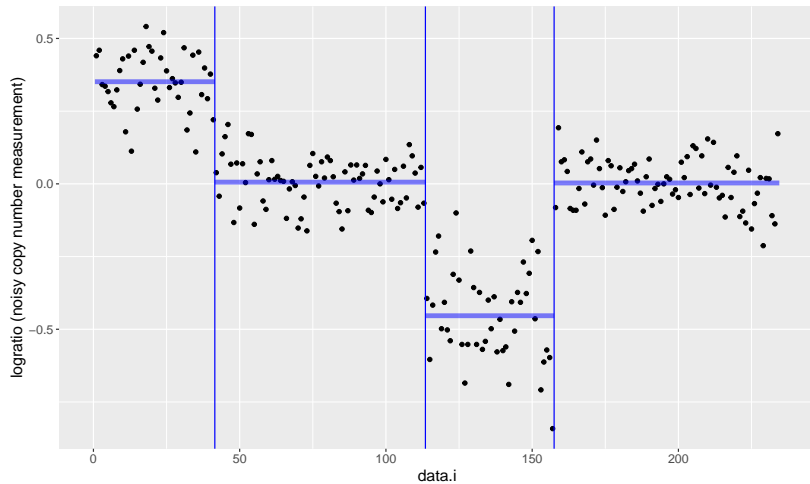
Find best single changepoint (two segments)



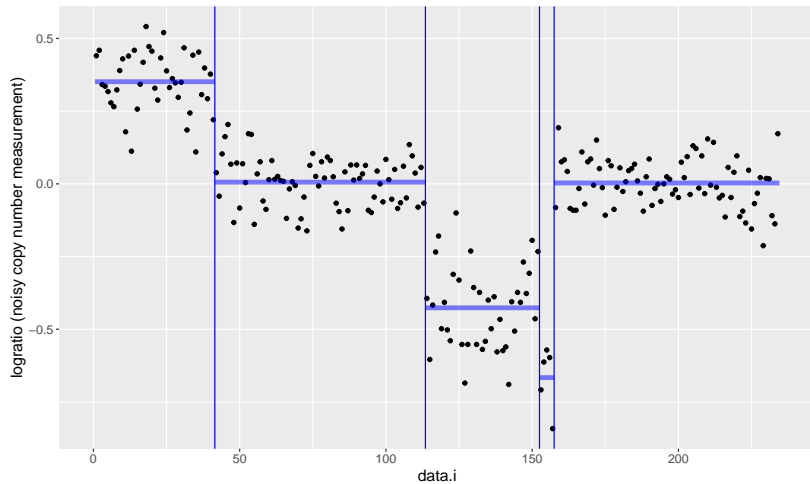
Find two changepoints (three segments)



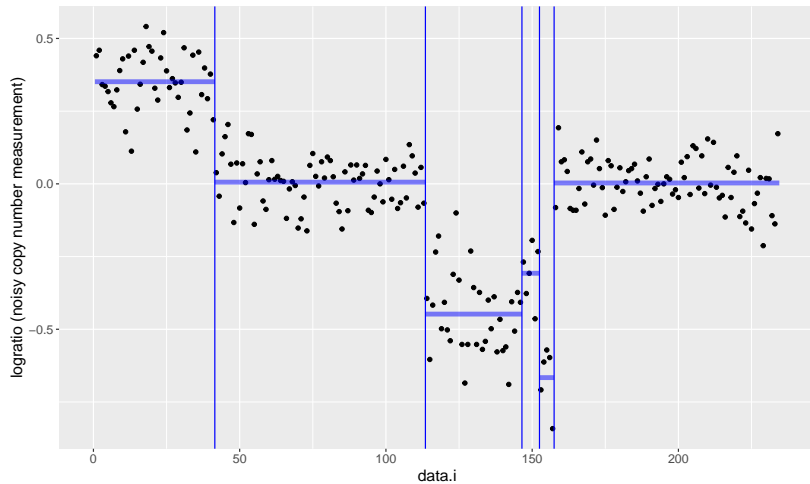
Find four segments



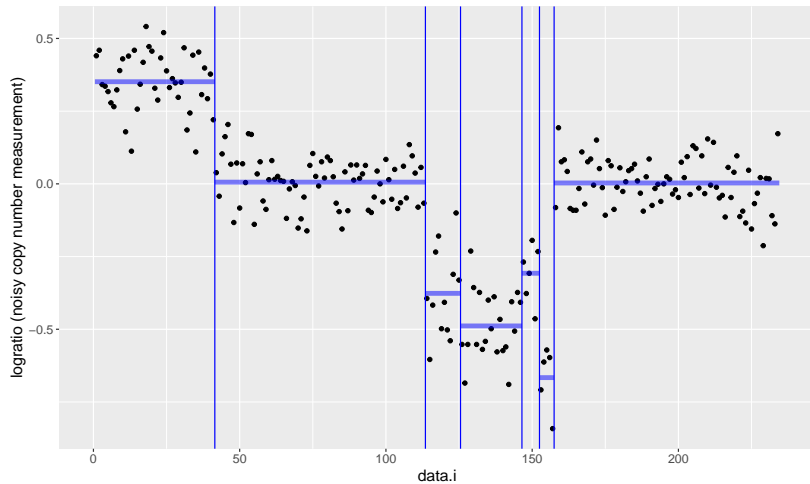
Find five segments



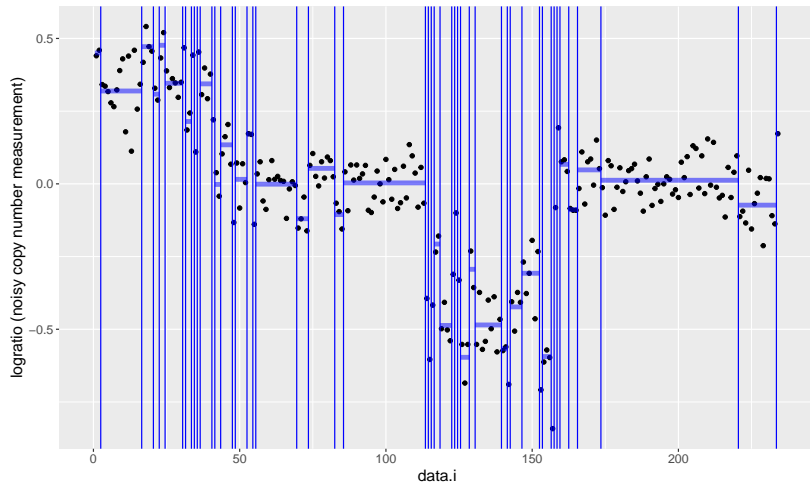
Find six segments



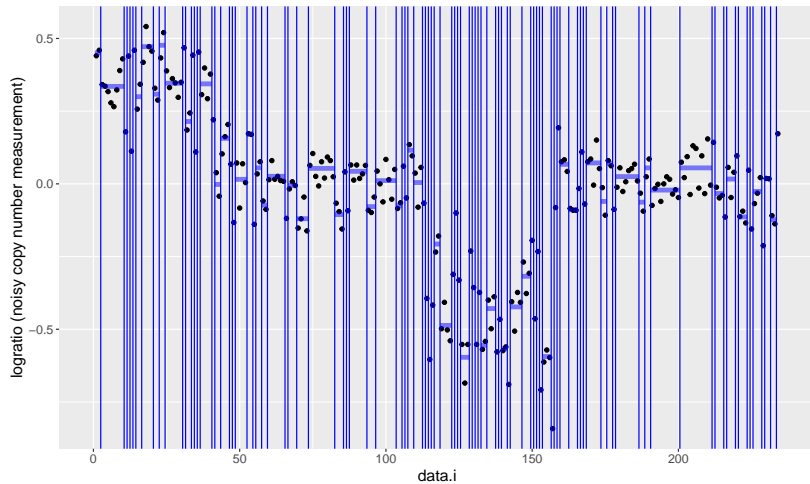
Find seven segments



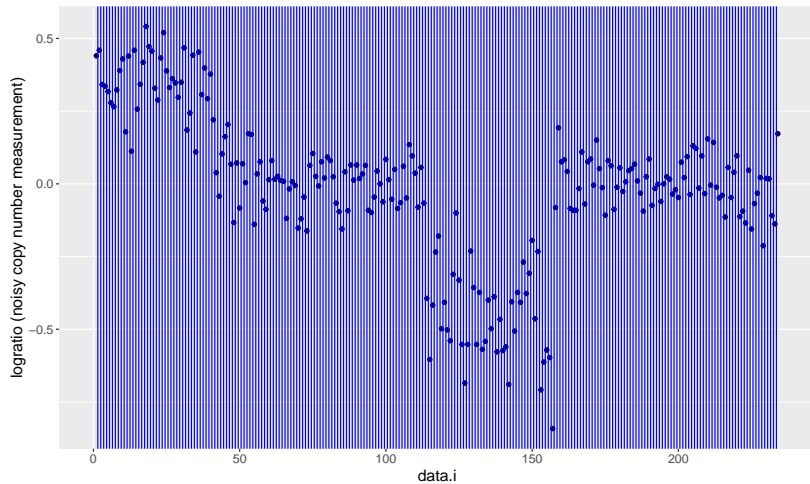
Find 50 segments



Find 100 segments

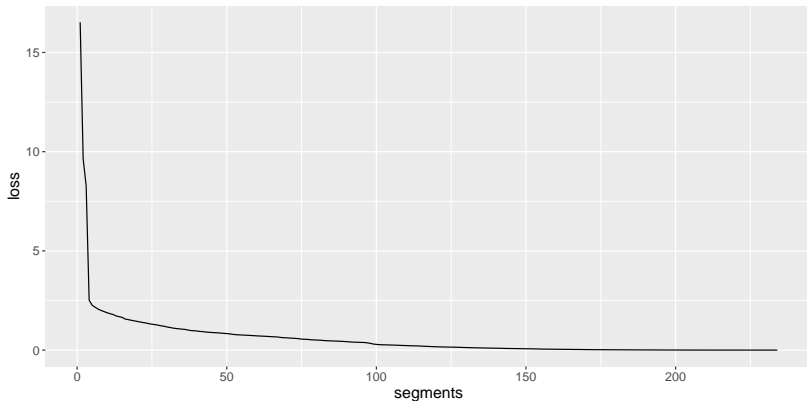


Largest model: 234 segments (changes everywhere)

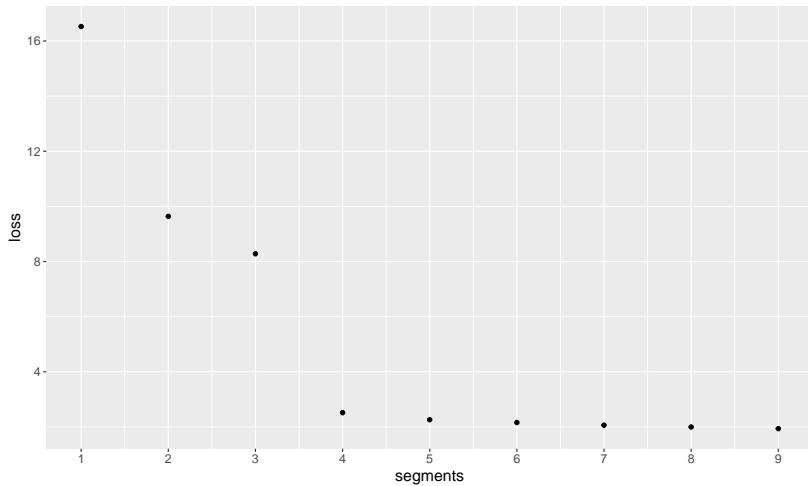


Error/loss function visualization

- ▶ Let $m^{(k)} \in \mathbb{R}^n$ be the mean vector with k segments.
- ▶ Error for k segments is defined as sum of squared difference between data x and mean $m^{(k)}$ vectors, $E_k = \sum_{i=1}^n (x_i - m_i^{(k)})^2$
- ▶ As in previous clustering models, kink in the error curve can be used as a simple model selection criterion.



Error/loss function zoom



Learning algorithm

- ▶ Start with one segment, then repeat:
- ▶ Compute loss of each possible split.
- ▶ Choose split which results in largest loss decrease.
- ▶ If $s = \sum_{i=1}^n x_i$ is the sum over n data points, then the mean is s/n and the square loss (from 1 to n) is

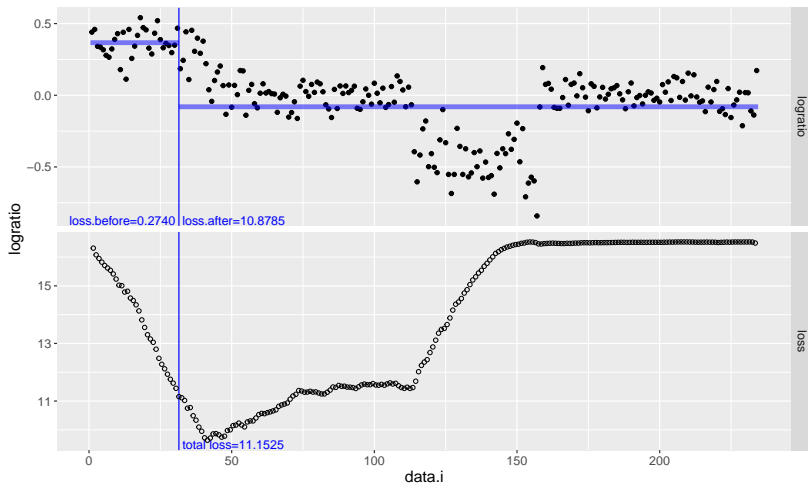
$$L_{1,n} = \sum_{i=1}^n (x_i - s/n)^2 = \sum_{i=1}^n [x_i^2] - 2(s/n)s + n(s/n)^2$$

- ▶ Given cumulative sums, and a split point t , we can compute square loss from 1 to t , $L_{1,t}$, and from $t+1$ to n , $L_{t+1,n}$, in constant $O(1)$ time.
- ▶ We can minimize over all changepoints t in linear $O(n)$ time,

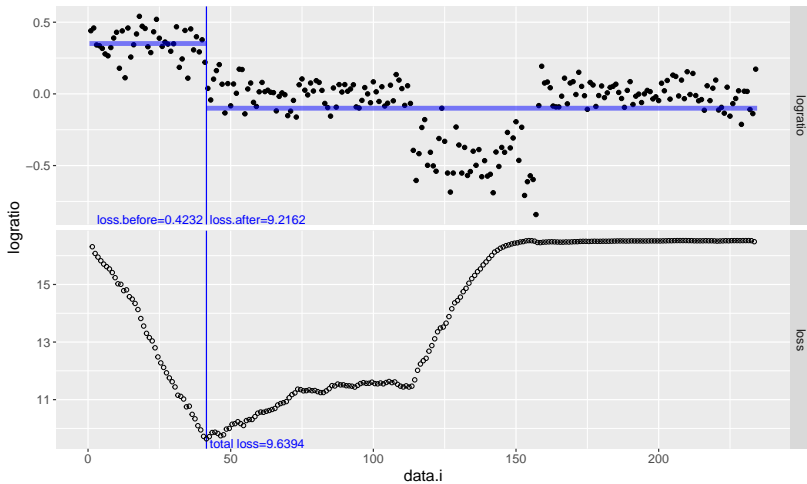
$$\min_{t \in \{1, \dots, n-1\}} L_{1,t} + L_{t+1,n}$$

First step of binary segmentation

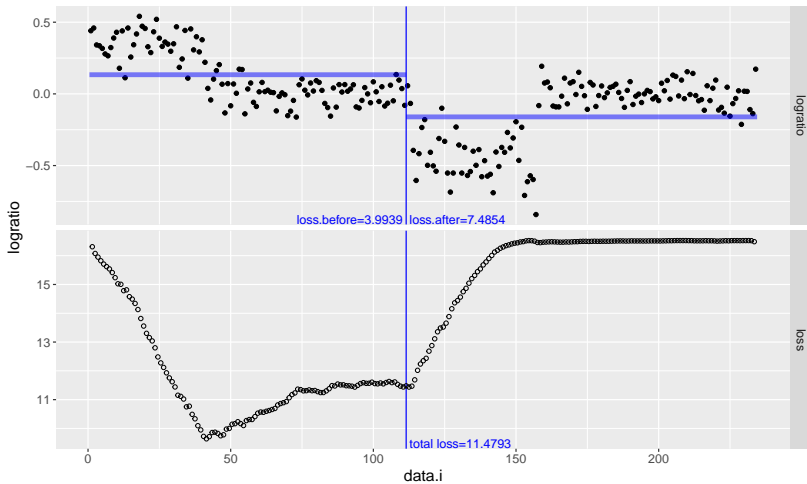
```
## Warning: Using `size` aesthetic for lines was deprecated  
## i Please use `linewidth` instead.  
## This warning is displayed once every 8 hours.  
## Call `lifecycle::last_lifecycle_warnings()` to see where
```



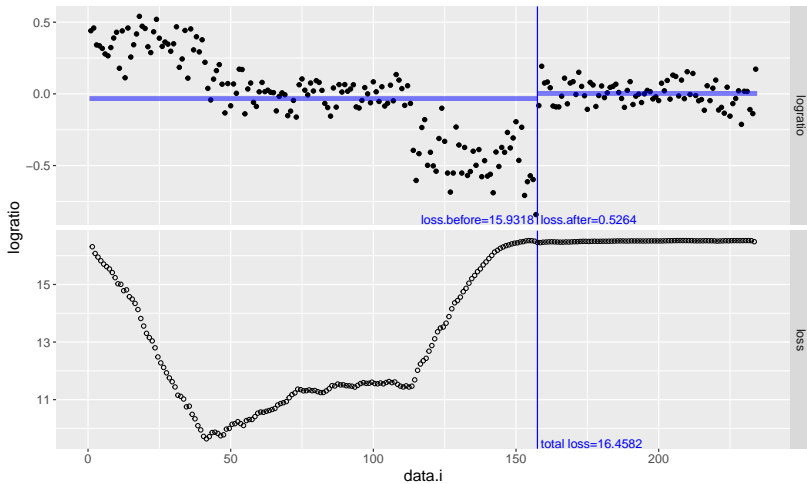
First step of binary segmentation



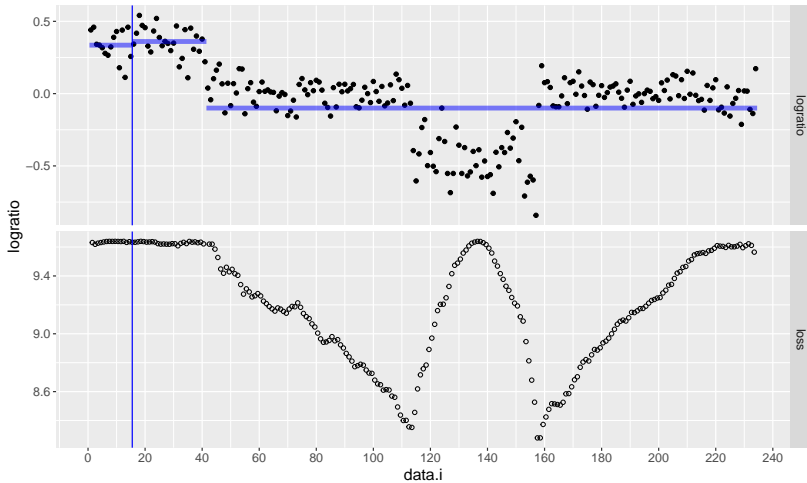
First step of binary segmentation



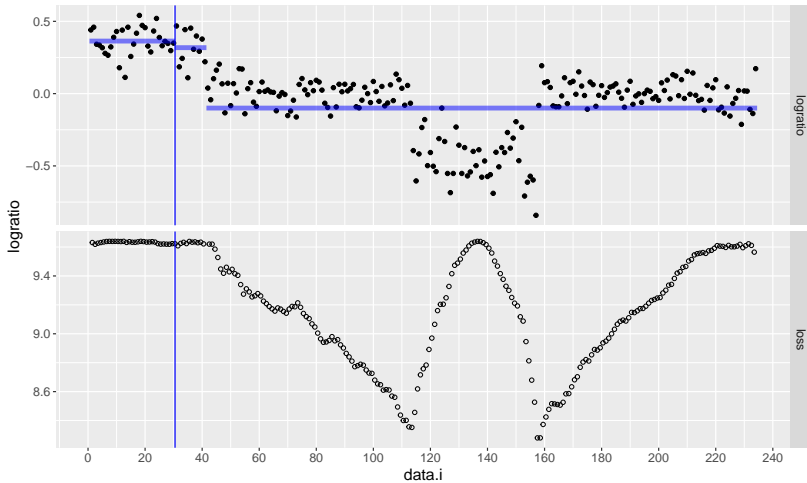
First step of binary segmentation



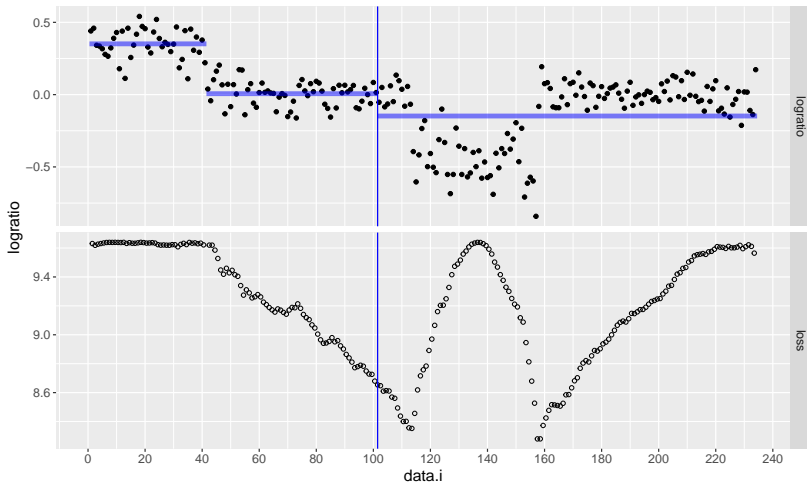
Second step of binary segmentation



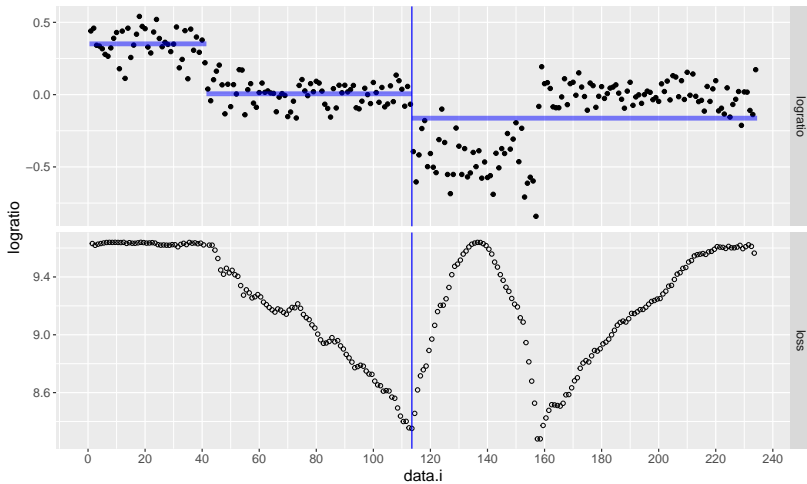
Second step of binary segmentation



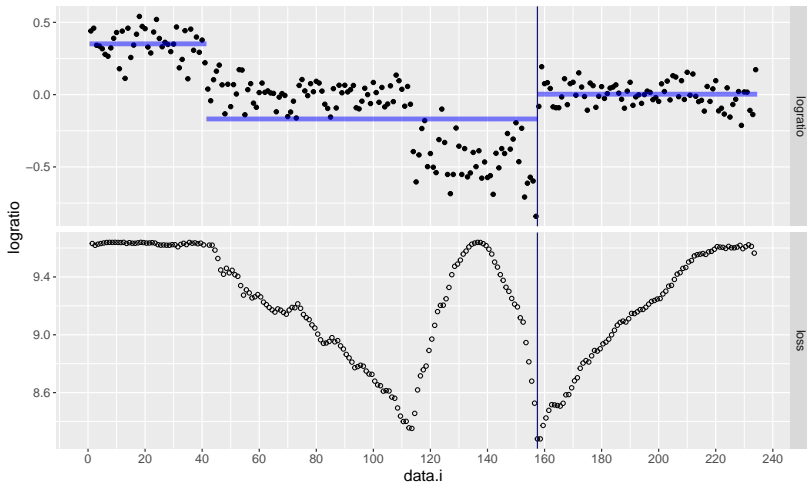
Second step of binary segmentation



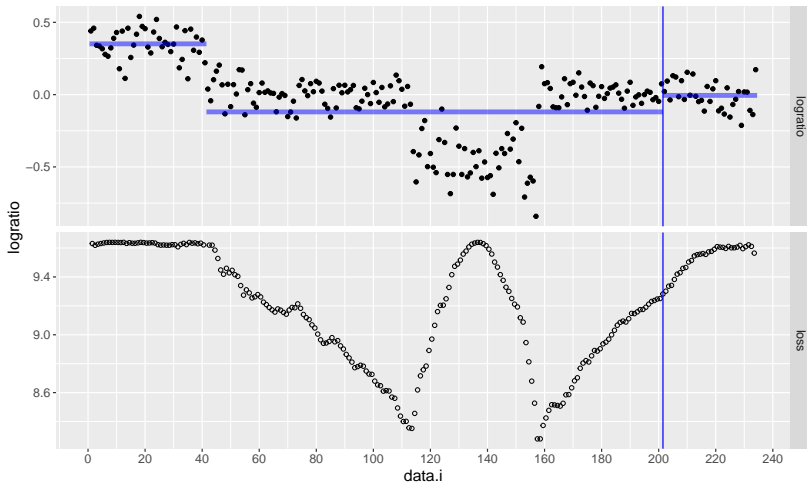
Second step of binary segmentation



Second step of binary segmentation

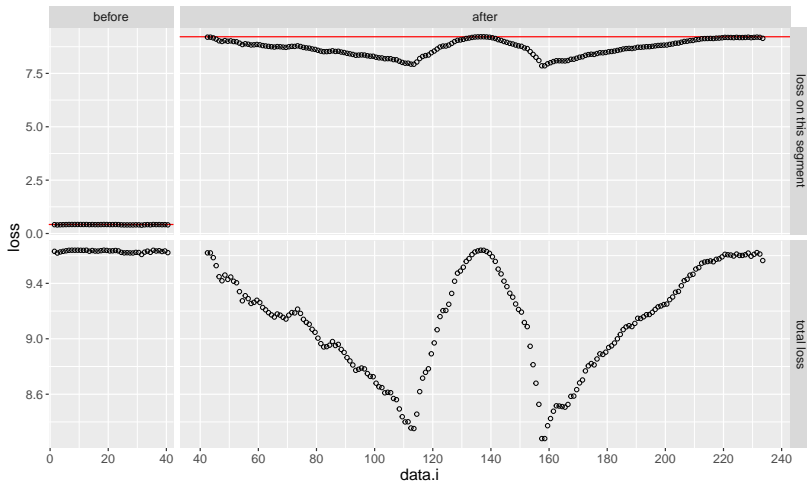


Second step of binary segmentation



Efficient loss computation

- Minimization can be performed by choosing the split with loss (black point) which maximizes the decrease in loss with respect to previous model (red, with no split).



Learning algorithm, implementation details

First compute the vectors of cumulative sums of data and squares, $y_1 = z_1 = 0, y_t = \sum_{i=1}^{t-1} x_i, z_t = \sum_{i=1}^{t-1} x_i^2$, for all $t \in \{2, \dots, n+1\}$.

Assume there is some set \mathcal{S} of segments that could be split, each $(j, e) \in \mathcal{S}$ is a segment start j and end e (both in $1, \dots, n$).

Then the next segment to split (j, e) , and best split point t , are defined by the best loss decrease,

$$\max_{(j,e) \in \mathcal{S}} \underbrace{L_{j,e}}_{\text{loss before split}} - \min_{t \in \{j, \dots, e-1\}} \underbrace{L_{j,t} + L_{t+1,e}}_{\text{loss after split}}$$

Use the cumsum trick to compute loss in constant time,

$$\sum_{i=j}^t x_i = y_{t+1} - y_j.$$

$$L_{j,t} = z_{t+1} - z_j - (y_{t+1} - y_j)^2 / (t - j + 1).$$

Learning algorithm, recursion/pseudo-code

Notation. Let $D_{j,e}(t) = L_{j,t} + L_{t+1,e} - L_{j,e}$ be the loss difference after splitting segment (j, e) at t , and let

$f(j, e) = \min, \arg \min_{t \in \{j, \dots, e-1\}} D_{j,e}(t)$ be the best loss difference/split on segment (j, e) .

Initialization. Let $\mathcal{L}_1 = L_{1,n}$ be the loss with one segment, and let $\mathcal{S}_1 = \{(1, n, f(1, n))\}$ be the initial segment to split.

Recursion. For all $k \in \{2, \dots, K\}$: (max segments $K \leq n$)

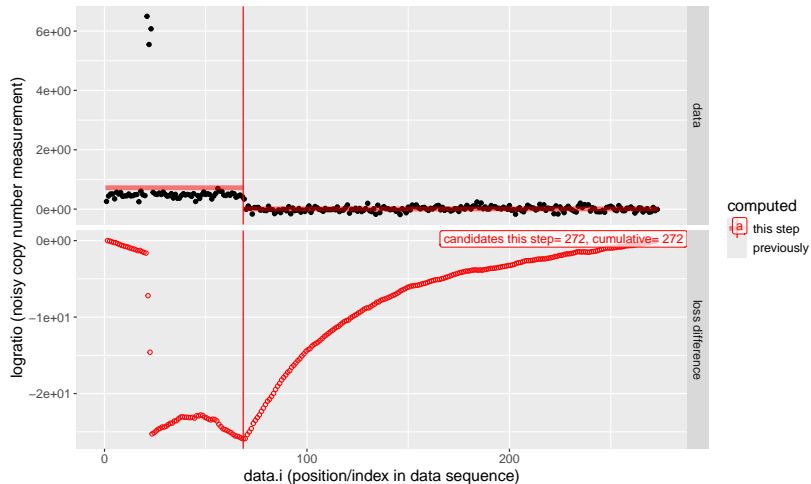
- ▶ $j_k^*, e_k^*, d_k^*, t_k^* = \arg \min_{(j,e,d,t) \in \mathcal{S}_{k-1}} d$ (best segment to split)
- ▶ $\mathcal{L}_k = \mathcal{L}_{k-1} + d_k^*$, (loss)
- ▶ $\mathcal{N}_k = \{(j_k^*, t_k^*), (t_k^* + 1, e_k^*)\}$ (new segments)
- ▶ $\mathcal{V}_k = \{(j, e, f(j, e)) \mid (j, e) \in \mathcal{N}_k, j < e\}$ (splittable segments)
- ▶ $\mathcal{S}_k = [\mathcal{S}_{k-1} \setminus (j_k^*, e_k^*, d_k^*, t_k^*)] \cup \mathcal{V}_k$ (segments to search)

Modification for min segment length

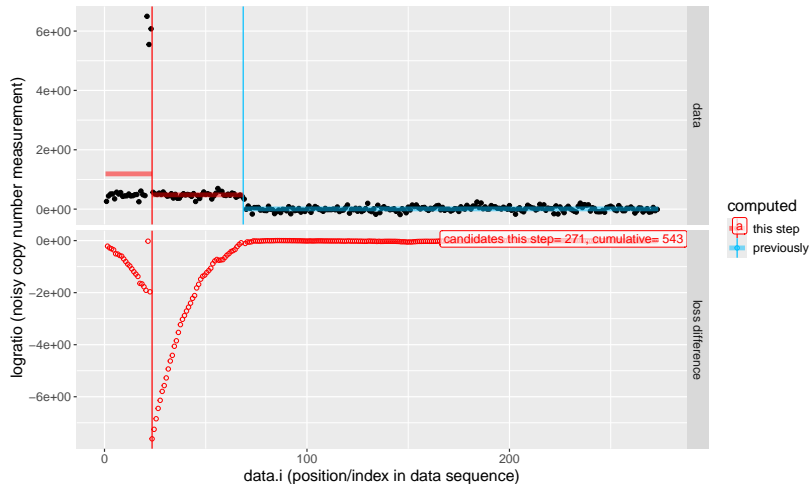
Sometimes there is prior knowledge that there should be no segments with fewer data points than $\ell \in \{1, 2, \dots\}$, and in that case there is a simple modification:

- ▶ $f(j, e) = \min, \arg \min_{t \in \{j+\ell-1, \dots, e-\ell\}} D_{j,e}(t)$ (best split)
- ▶ $\mathcal{V}_k = \{(j, e, f(j, e)) \mid (j, e) \in \mathcal{N}_k, e - j + 1 \geq 2\ell\}$ (splittable segments)

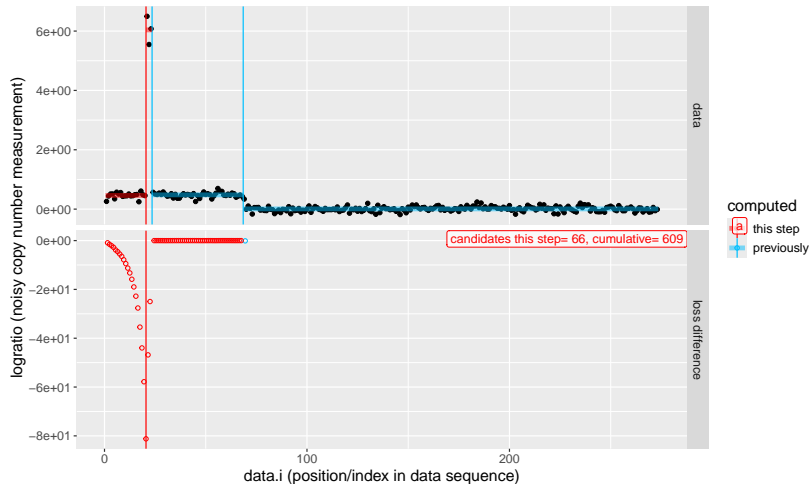
Visualization of computations at each iteration



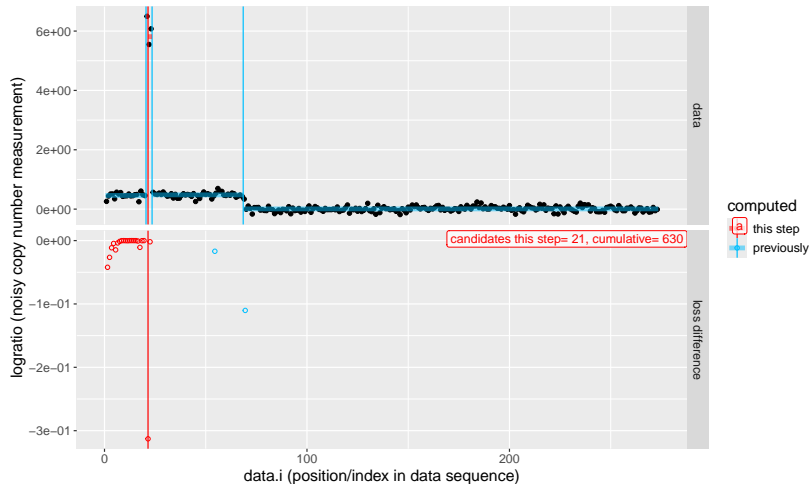
Visualization of computations at each iteration



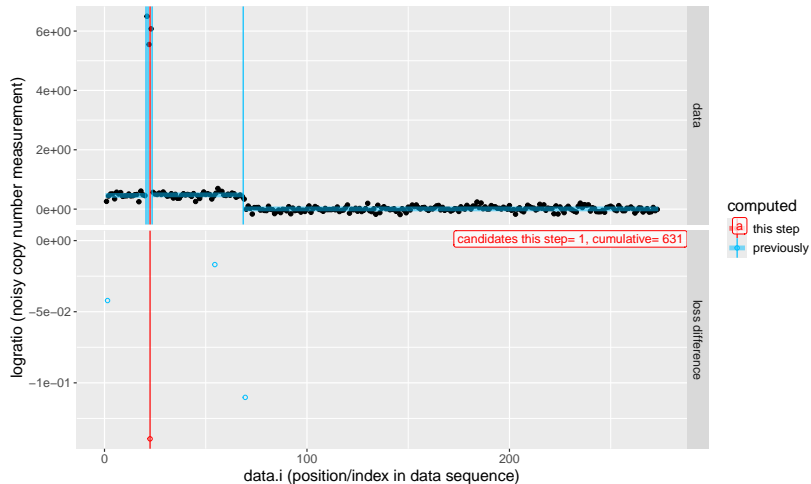
Visualization of computations at each iteration



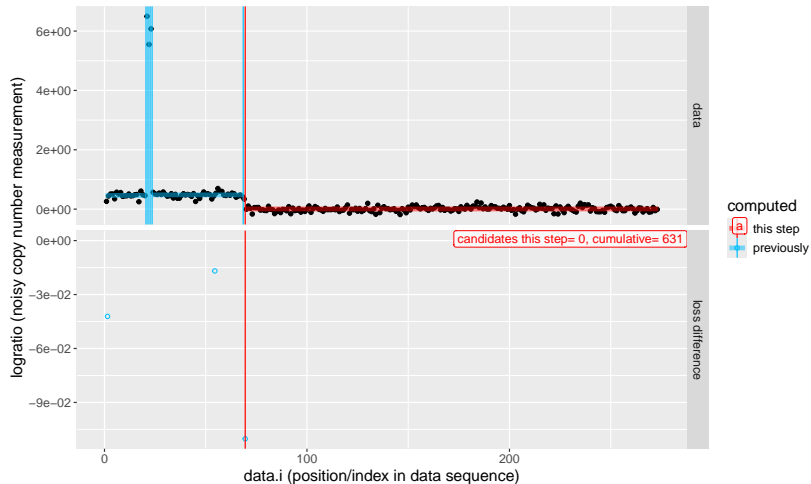
Visualization of computations at each iteration



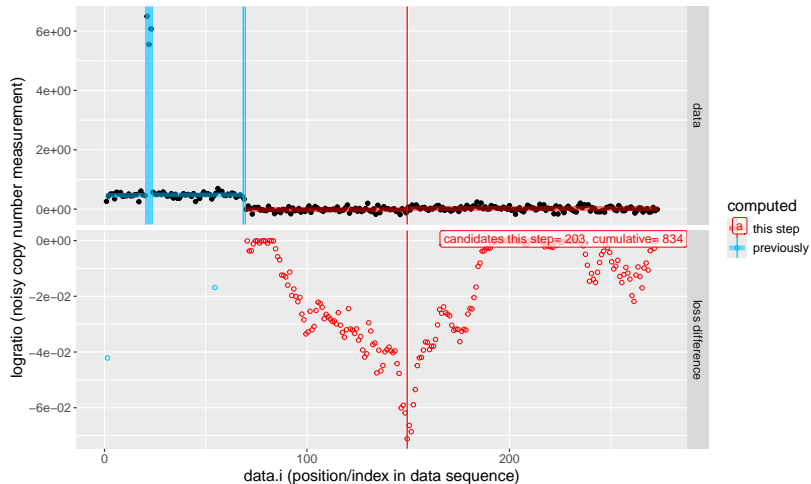
Visualization of computations at each iteration



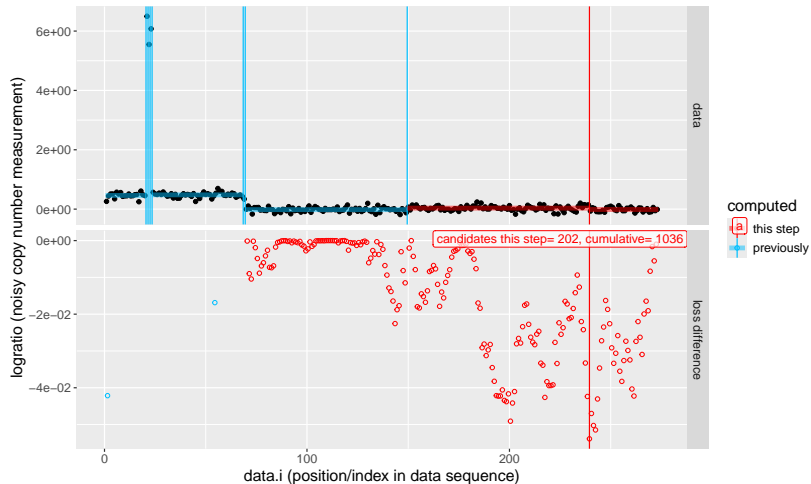
Visualization of computations at each iteration



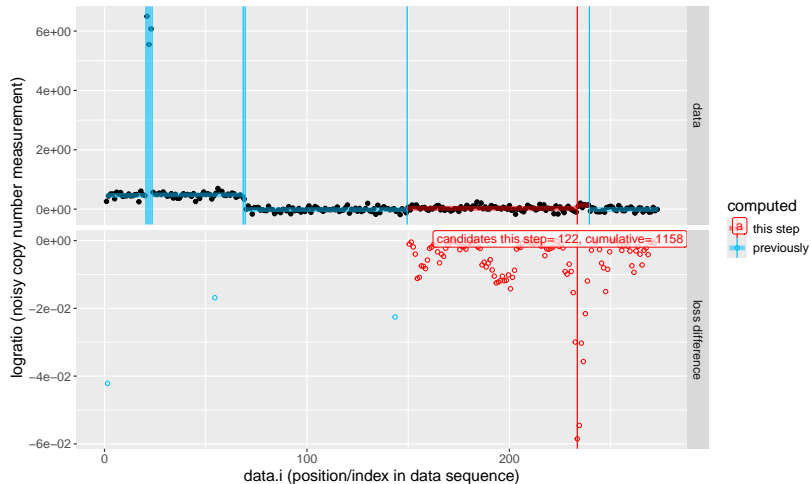
Visualization of computations at each iteration



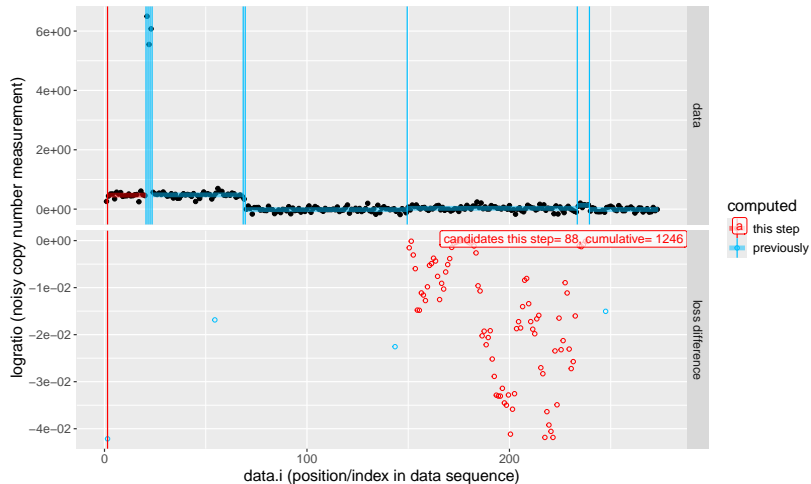
Visualization of computations at each iteration



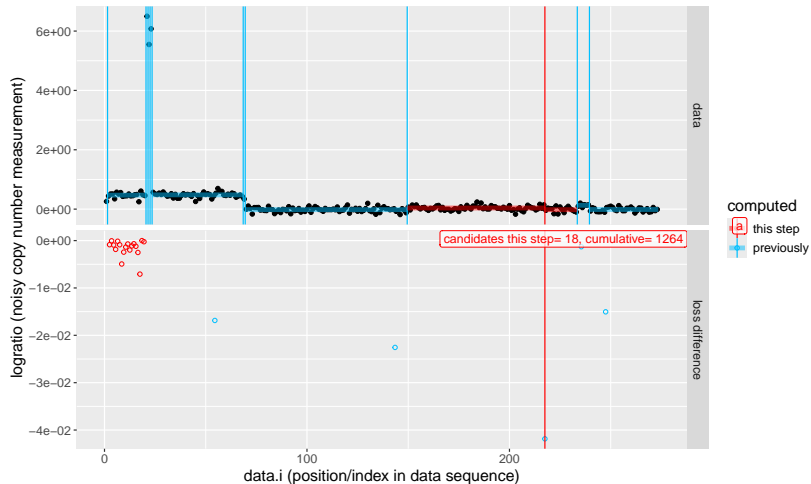
Visualization of computations at each iteration



Visualization of computations at each iteration



Visualization of computations at each iteration



Complexity analysis

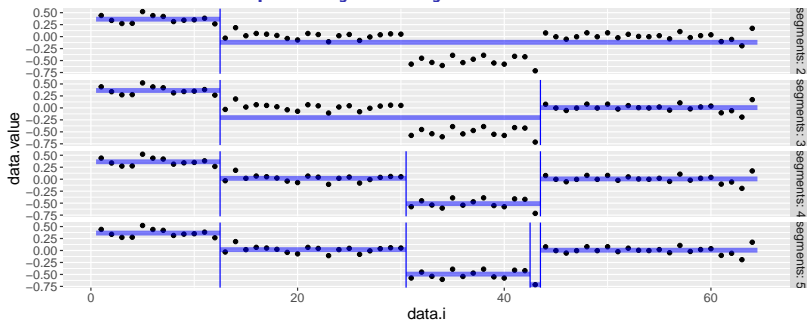
- ▶ Assume n data and K segments.
- ▶ Computing best loss decrease and split point for a segment with t data takes $O(t)$ time.
- ▶ Keep a list of segments which could be split, sorted by loss decrease values.
- ▶ Best case is when segments get cut in half each time, $O(n \log K)$ time. (minimize number of possible splits for which we have to recompute loss)
- ▶ Worst case is when splits are very unequal $(1, t - 1)$, $O(nK)$ time. (maximize number of possible splits for which we have to recompute loss)

Detailed complexity analysis

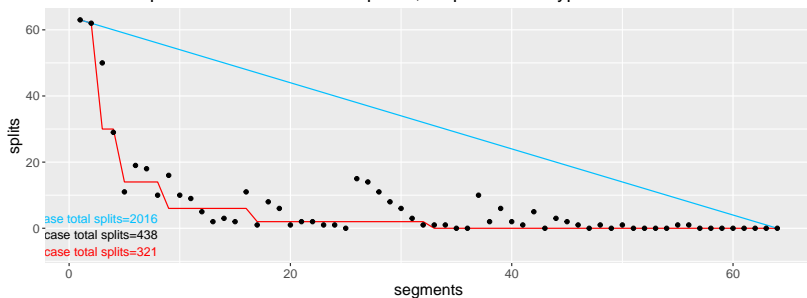
- ▶ Let $n = 2^J$ for some $J \in \{1, 2, \dots\}$, for example $J = 6 \Rightarrow n = 64$.
- ▶ For any $j \in \{1, \dots, J + 1\}$ if we do $K = 2^{j-1}$ iterations then how many split cost values to compute?
- ▶ Best case:
 $nj - 2^j + 1 = n(1 + \log_2 K) - K/2 + 1 \Rightarrow O(n \log K)$.
- ▶ Worst case: $nK - K(1 + K)/2 \Rightarrow O(nK)$.

j	K	best	total	worst	total
1	1	$n - 1 = 63$	$n - 1 = 63$	$n - 1 = 63$	$n - 1 = 63$
2	2	$n - 2 = 62$	$2n - 3 = 125$	$n - 2 = 62$	$2n - 3 = 125$
	3	$n/2 - 2 = 30$		$n - 3 = 61$	$3n - 6 = 186$
3	4	$n/2 - 2 = 30$	$3n - 7 = 185$	$n - 4 = 60$	$4n - 10 = 246$
⋮	⋮	⋮	⋮	⋮	⋮
4	8	$n/4 - 2 = 14$	$4n - 15 = 241$	$n - 8 = 56$	$8n - 36 = 476$
⋮	⋮	⋮	⋮	⋮	⋮
7	64	$n/32 - 2 = 0$	$7n - 128 = 321$	$n - 64 = 0$	$64n - 2080 = 2016$

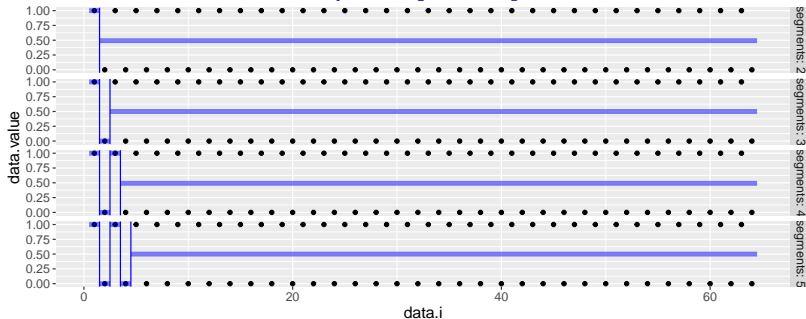
Real data time complexity analysis



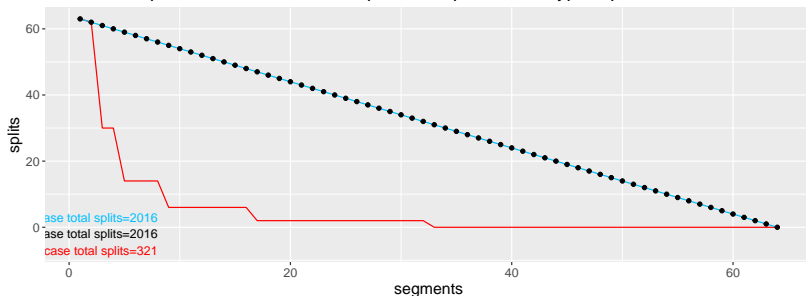
Number of splits for which loss is computed, empirical data type=real



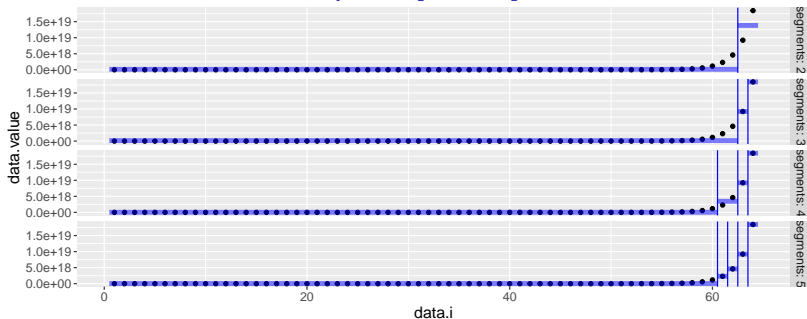
Synthetic data time complexity analysis



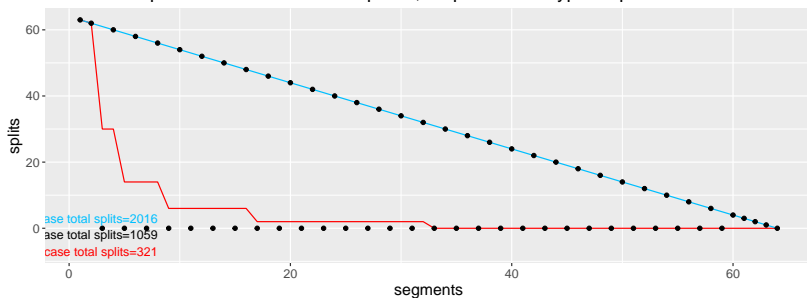
Number of splits for which loss is computed, empirical data type=up.and.down



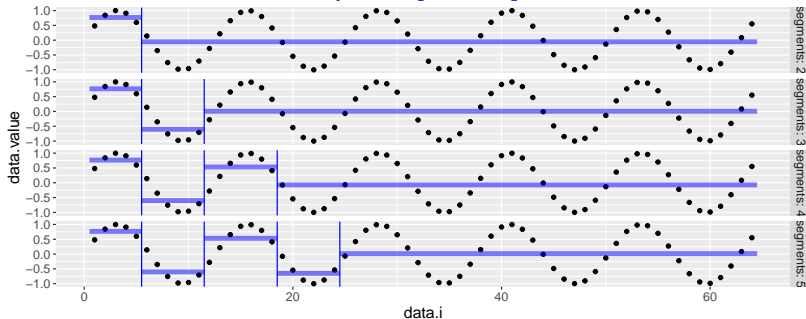
Synthetic data time complexity analysis



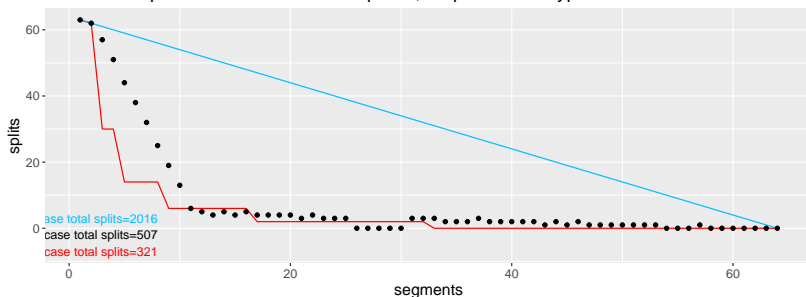
Number of splits for which loss is computed, empirical data type=exponential



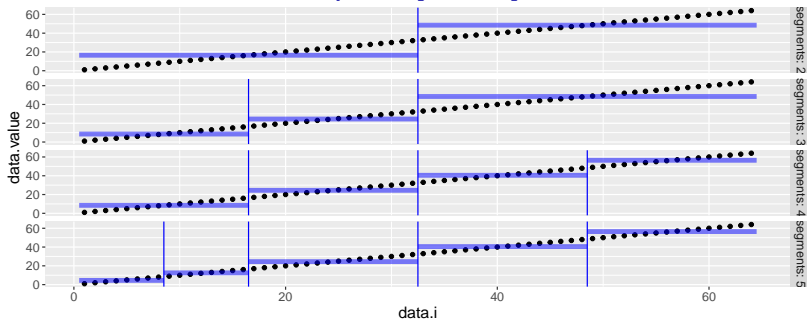
Synthetic data time complexity analysis



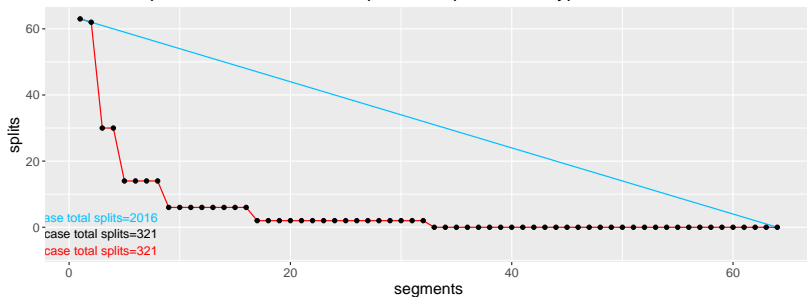
Number of splits for which loss is computed, empirical data type=sin



Synthetic data time complexity analysis

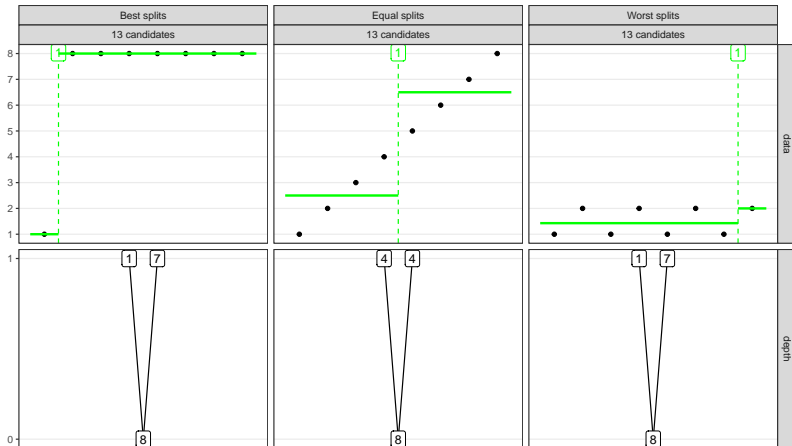


Number of splits for which loss is computed, empirical data type=linear



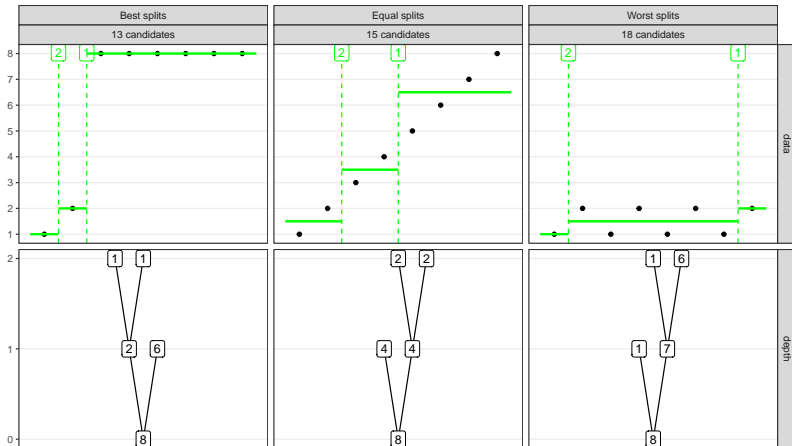
Synthetic data time complexity, vary max segments

N_data=8, Max segments=2



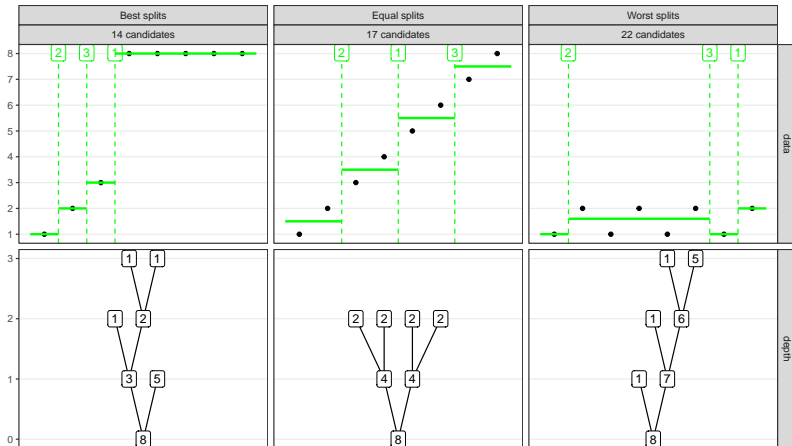
Synthetic data time complexity, vary max segments

N_data=8, Max segments=3



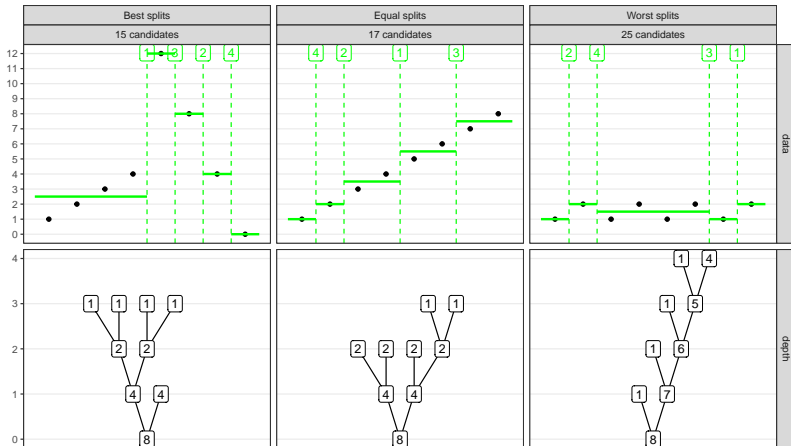
Synthetic data time complexity, vary max segments

N_data=8, Max segments=4



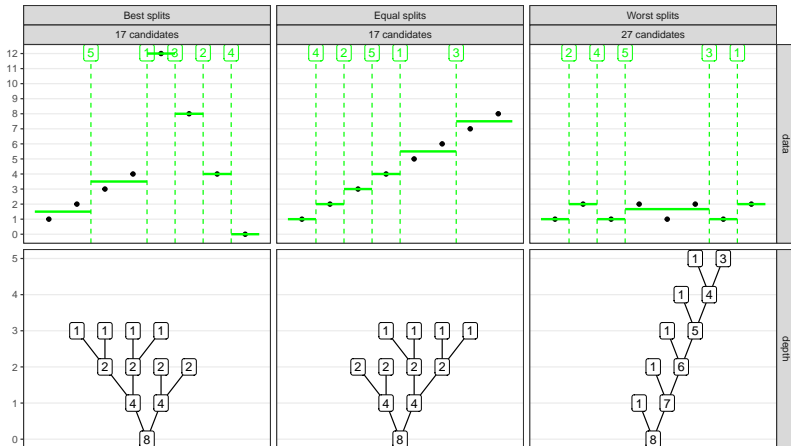
Synthetic data time complexity, vary max segments

N_data=8, Max segments=5



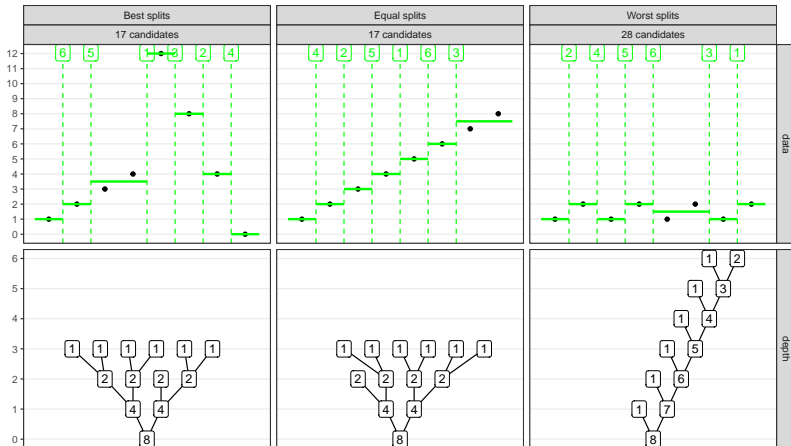
Synthetic data time complexity, vary max segments

N_data=8, Max segments=6



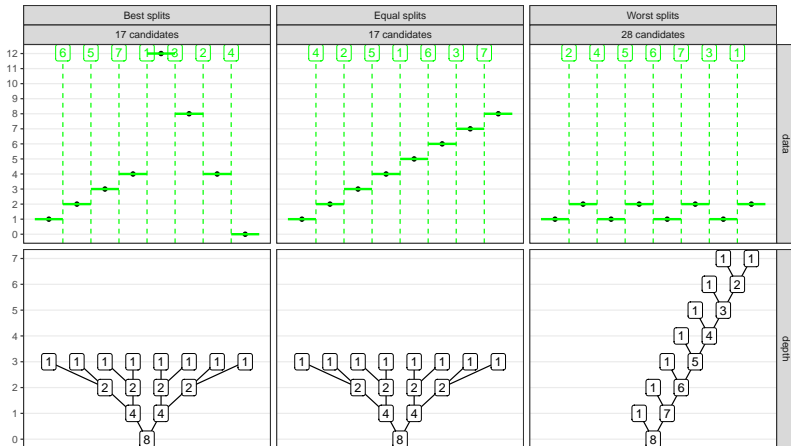
Synthetic data time complexity, vary max segments

N_data=8, Max segments=7

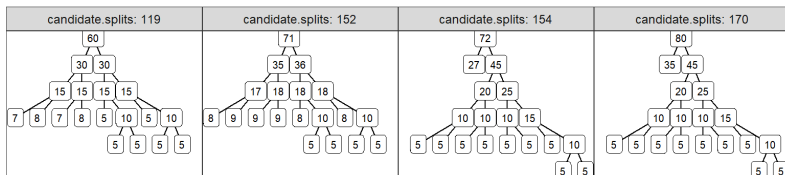


Synthetic data time complexity, vary max segments

N_data=8, Max segments=8

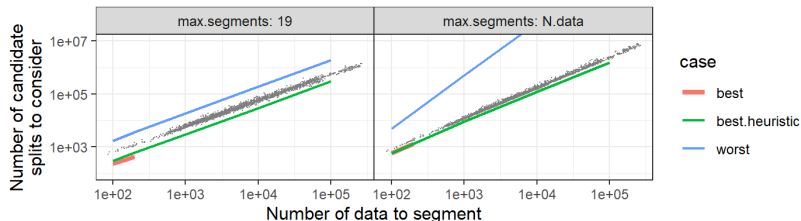


Optimal binary trees



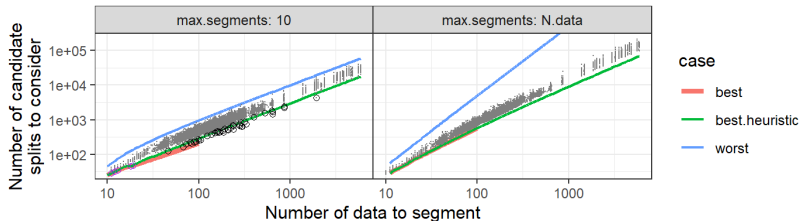
- ▶ $n \in \{60, 71, 72, 80\}$ data, min segment length $m = 5$, and number of splits/iterations $K = 9$.
- ▶ Smaller $n \in \{60, 71\}$ values result in a balanced first split,
- ▶ Larger $n \in \{72, 80\}$ values result in an unbalanced first split (one small child with no splits, one large child with all remaining splits).
- ▶ Hocking arXiv:2410.08654 Finite Sample Complexity Analysis of Binary Segmentation propose algorithm to compute optimal binary tree.
- ▶ Is binary segmentation asymptotically optimal speed in real data?

Empirical number of candidates (Poisson loss)



- ▶ 2752 real genomic count data sets from McGill benchmark of data size n from 87 to 263169, using binary segmentation with the Poisson loss.
- ▶ Number of candidate splits to consider in real data (grey dots) achieves the asymptotic best case, $O(n \log n)$.

Empirical number of candidates (Square loss)



- ▶ 13721 real genomic data sets from neuroblastoma benchmark of data size n from 11 to 5937, using binary segmentation with the square loss.
- ▶ Number of candidate splits achieves the asymptotic best case, $O(n \log n)$, and in 45 instances (black circles) requires fewer candidate splits than predicted by the best case heuristic.
- ▶ For max segments = 10, we used dynamic programming to compute the best case number of splits for all data sizes between 11 and 100 (orange line), and the heuristic (green line) was exact for only 5 data sizes $n \in \{11, 12, 13, 18, 19\}$ (purple circles).

Analysis of insert time and storage (STL list)

To store previously computed best loss/split for each segment, use C++ Standard template library list as baseline.

- ▶ If list has p items then insert takes $O(1)$ time.
- ▶ Find best segment to split: $O(p)$ time.
- ▶ Total $O(K^2)$ time for K iterations (equal splits), larger than $O(n \log K)$ time for computing candidate loss values.

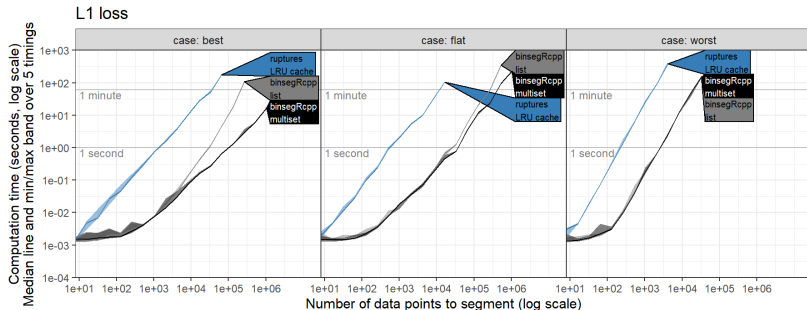
splits K	items in list (equal splits)	items in list (unequal splits)
1	1	1
2	2	1
3	3	1
\vdots	\vdots	\vdots
32	32	1
33	31	1
34	30	1
\vdots	\vdots	\vdots
62	2	1
63	1	1

Analysis of insert time and storage (STL multiset)

To achieve asymptotic best case timings, use a C++ Standard template library multiset, keyed by loss decrease. If multiset has p items then insert takes $O(\log p)$ time. Below: inserts column shows p for each insert, and size column shows p after inserts. Total $-\log(K-1) + \sum_{p=1}^{K-1} 2 \log p \in O(K \log K)$ time over all inserts, smaller than $O(n \log K)$ time for split computation.

iteration	K	equal splits		unequal splits	
		inserts	size	inserts	size
1		0	1	0	1
2		0,1	2	0	1
3		1,2	3	0	1
\vdots		\vdots	\vdots	\vdots	\vdots
32		30,31	32	0	1
33			31	0	1
34			30	0	1
\vdots		\vdots	\vdots	\vdots	\vdots
62			2	0	1
63			1	0	1

Timings using L1 loss



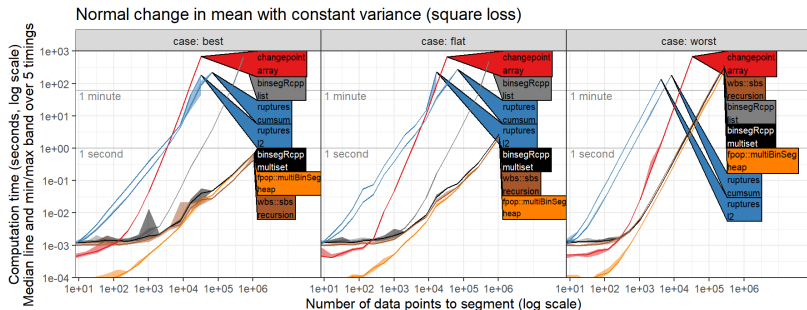
- ▶ Number of segments grows with data size, $K = O(n)$.
- ▶ Best case: binsegRcpp multiset is $O(n \log n)$, asymptotically faster than binsegRcpp list, $O(n^2)$.
- ▶ ruptures is significantly slower (100x).
- ▶ Worst case: all algorithms are quadratic, because that is the number of candidate change-points that must be considered.

Comparing implementations of binary segmentation

package function version	binsegRcpp binseg 2022.3.29	changeoint cpt.mean 2.2.3	wbs sbs 1.4	fpop multiBinSeg 2019.8.26	ruptures Binseg 1.1.9	blockcpd fit_blockcpd 1.0.0
weights	yes	no	no	no	no	no
max segs	yes	yes	no	yes	yes	yes
dim	one	one	one	multi	multi	multi
correct	yes	no	yes	yes	yes	
losses	5	6	1	1	10	5
language	C++	C	C	C++	Python	C++
storage	STL multiset	arrays	recursion	heap	LRU cache	heap
space	$O(S)$	$O(S^2)$	$O(S)$	$O(S)$	$O(S)$	$O(S)$
cumsum	yes	yes	yes	yes	no	yes
best	$O(N \log N)$	$O(N^3)$	$O(N \log N)$	$O(N \log N)$	$> O(N \log N)$	$O(N \log N)$
worst	$O(N^2)$	$O(N^3)$	$O(N^2)$	$O(N^2)$	$O(N^2)$	$O(N^2)$
CV	yes	no	no	no	no	no
params	all	one	no	no	no	one

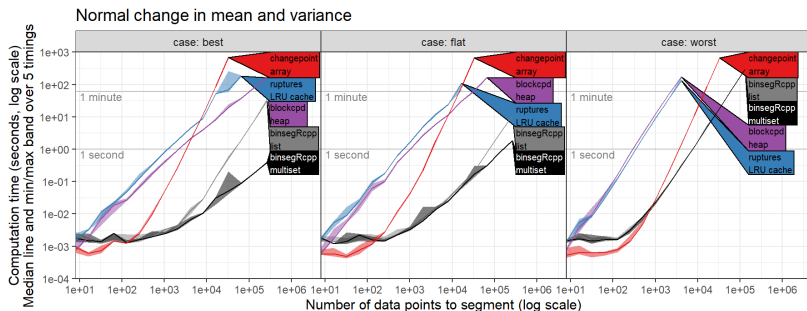
Hocking arXiv:2410.08654 Finite Sample Complexity Analysis of Binary Segmentation.

Timings using square loss

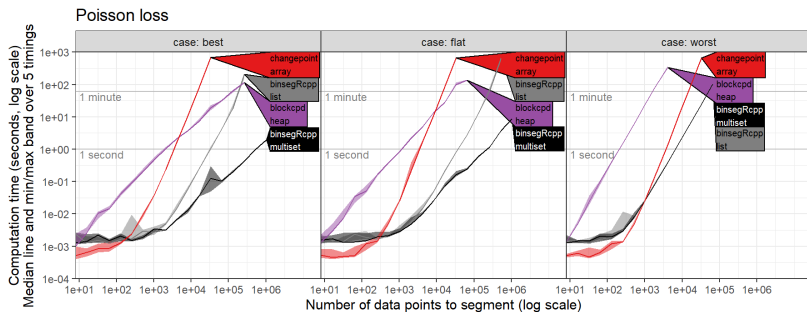


- ▶ `binsegRcpp` map, `wbs::sbs`, `fpop::multiBinSeg` optimal: $O(n \log n)$ time in best case.
- ▶ `ruptures` is between $O(n \log n)$ and $O(n^2)$ time, but with large constant factors.
- ▶ `binsegRcpp` list has larger slope: $O(n^2)$ time.
- ▶ `changepoint` has even larger slope: $O(n^3)$ time.

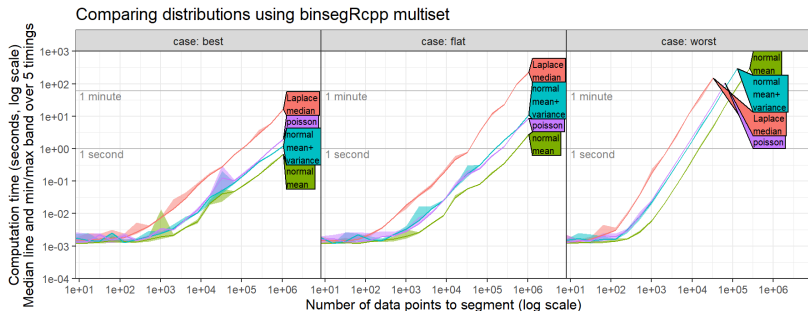
Timings using Gaussian change in mean and variance model



Timings using Poisson loss

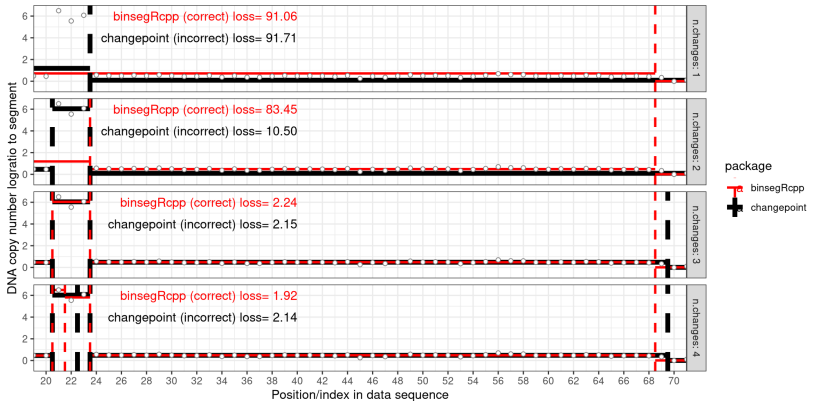


Comparing loss functions, binsegRcpp multiset



- Laplace (log-linear) is somewhat slower than others (linear).

Accuracy of binsegRcpp and changepoint



- ▶ Real data set for which changepoint does not compute the correct model.
- ▶ Loss should be minimized at each iteration.

Conclusions

- ▶ Binary segmentation is an important algorithm for change-point detection in sequential data.
- ▶ Optimal binary trees used to determine best case number of candidates that the algorithm needs to consider.
- ▶ Empirical number of candidates in real data: same as best case, asymptotically.
- ▶ Proposed `binsegRcpp` R package provides C++ code which is asymptotically optimal speed, and correct.
- ▶ `install.packages("binsegRcpp")` in R.
- ▶ Future work: faster method for computing optimal binary trees?

Comparison with previous algorithms from clustering

- ▶ Binary segmentation has segment/cluster-specific mean parameter, as in K-means and Gaussian mixture models. These algorithms attempt optimization of an error function which measures how well the means fit the data (but are not guaranteed to compute the globally optimal/best model).
- ▶ Binary segmentation is deterministic (different from K-means/GMM which requires random initialization). It performs a sequence of greedy minimizations (as in hierarchical clustering).
- ▶ Binary segmentation defines a sequence of split operations (from 1 segment to N segments), whereas agglomerative hierarchical clustering defines a sequence of join operations (from N clusters to 1 cluster). Data with common segment mean must be adjacent in time/space; hierarchical clustering joins may happen between any pair of data points (no space/time dimension).

Possible exam questions

- ▶ Explain in detail one similarity and one difference between binary segmentation and k-means. (gaussian mixture models, hierarchical clustering)
- ▶ For a sequence of $n = 10$ data, we need to compute the loss for each of the 9 possible splits in the first iteration of binary segmentation. What is the number of splits for which we must compute the loss in the second/third steps? (best and worst case)