

# 1 Introductory notation

## 1.1 Markov and Lagrange values

Symbol  $\mathcal{M}$  denotes double-infinite sequences from  $\mathbb{N}^{\mathbb{Z}}$ :

$$\mathcal{M} = \dots a_{-2} a_{-1} a_0 a_1 a_2 \dots$$

I will use  $\lambda(\mathcal{M})$ ,  $\mu(\mathcal{M})$  and  $f(\mathcal{M})$  for Lagrange, Markov values and height function. Symbols  $\gamma$  and  $\delta$  denote the lhs and rhs of sequence  $\mathcal{M}$ :

$$\begin{aligned}\gamma(\mathcal{M}) &= [0; a_{-1}, a_{-2}, \dots], \\ \delta(\mathcal{M}) &= [0; a_1, a_2, \dots], \\ f(\mathcal{M}) &= a_0 + \gamma(\mathcal{M}) + \delta(\mathcal{M}).\end{aligned}$$

At last, symbols  $M$  and  $L$  denote the Markov and Lagrange spectra.

## 1.2 Centered sequence

**Definition.** A sequence  $\mathcal{M}$  is called **centered**, if

$$\mu(\mathcal{M}) = f(\mathcal{M}). \tag{1}$$

**Proposition.** Markov spectrum can be defined with only centered sequences:

$$\{\mu(\mathcal{M}) \mid \mathcal{M} \in \mathbb{N}^{\mathbb{Z}}\} = M = \{\mu(\mathcal{M}) \mid \mathcal{M} \text{ is centered} \}.$$

## 1.3 Rectangle

**Designation.** Denote by

$$\{a_{i_1}, a_{i_1+1}, \dots, a_{i_2}\} \quad (i_1 \leq 0 \leq i_2)$$

the set of double-infinite sequences  $\mathcal{M}$  with fixed terms  $a_{i_1}, a_{i_1+1}, \dots, a_{i_2}$  on the corresponding positions.

Terms  $a_s$  for  $s < i_1$  and  $s > i_2$  are arbitrary integers, chosen such that  $\mathcal{M}$  is centered and, maybe, satisfies some conditions.

Segments  $\Delta_1$ ,  $\Delta_2$  and  $\Delta$  are defined by the following equations:

$$\begin{aligned}\Delta_1 &= [\Delta'_1; \Delta''_1] = [\min \gamma(\mathcal{M}); \max \gamma(\mathcal{M})], \\ \Delta_2 &= [\Delta'_2; \Delta''_2] = [\min \delta(\mathcal{M}); \max \delta(\mathcal{M})], \\ \Delta &= [\Delta'; \Delta''] = a_0 + \Delta_1 + \Delta_2,\end{aligned} \tag{2}$$

where  $\mathcal{M}$  belongs to the set.

Note that we will use ' for the lower bound, and '' for the upper bound.

**Definition.** **Rectangle** is the segment  $\Delta$  with the set of sequences, defining it.

## 1.4 Horizontal rectangle

**Definition.** Call a rectangle  $\Delta$  **horizontal**, if

$$|\Delta_1| \geq |\Delta_2|. \quad (3)$$

In (3) we allow terms  $a_s$  for  $s < i_1$  and  $s > i_2$  to be integers  $\{1, 2, 3\}$ , regardless of the requirement that sequences  $\mathcal{M} \in \Delta$  are centered.

In other words,  $\Delta$  is horizontal, if and only if

$$|[0; a_{-1}, \dots, a_{i_1}, \overline{3}, \overline{1}] - [0; a_{-1}, \dots, a_{i_1}, \overline{1}, \overline{3}]| \geq |[0; a_1, \dots, a_{i_2}, \overline{3}, \overline{1}] - [0; a_1, \dots, a_{i_2}, \overline{1}, \overline{3}]|.$$

Clearly, we can always obtain a horizontal rectangle out of the vertical one, as we can reindex the sequence in the opposite direction.

## 1.5 Subrectangle

Consider a rectangle  $\Delta$ , set by the sequence center

$$\{a_{i_1}, a_{i_1+1}, \dots, a_{i_2}\}.$$

We will use a **shorter notation** for subrectangles, produced by setting integers  $a_i$  for  $i < i_1$  or  $i > i_2$ :

$$\{b_\ell \dots b_1, c_1 \dots c_r\} := \{b_\ell \dots b_1 a_{i_1} \dots a_{i_2} c_1 \dots c_r\}.$$

For example:

$$\{213, 3\} := \{213 a_{i_1} \dots a_{i_2} 3\}, \quad (\text{ex.1})$$

$$\{2, 0\} := \{2 a_{i_1} \dots a_{i_2}\}. \quad (\text{ex.2})$$

We will also shorter the notation (2): lhs and rhs are  $\Delta_1(312)$  and  $\Delta_2(3)$  for subrectangle (ex.1) and  $\Delta_1(2)$  and  $a_2$  for (ex.2).

## 1.6 Geometrical interpretation

Consider the mapping

$$\begin{aligned} \tilde{h} : \mathbb{N}^{\mathbb{Z}} &\rightarrow \mathbb{R}^2, \\ \tilde{h}(\mathcal{M}) &= (\gamma(\mathcal{M}); \delta(\mathcal{M})). \end{aligned}$$

In these terms, the Markov spectrum  $M$  is the projection of some subset  $\mathcal{S} \subset C_4 \times C_4$  onto the diagonal.

Then **rectangle**  $\Delta$  is indeed a rectangle  $\Delta_1 \times \Delta_2$  and **subrectangles** are its subrectangles.

We will consider a family of rectangles whose projections cover the beginning of Hall's Ray.

Then we will present the algorithm to split rectangle into subrectangles so that their projections cover the projection of initial rectangle.

When we say that rectangles intersect, we, however, mean that their projections intersect.

The more «squarish» the rectangle, the easier the step.

That's why we will bound the aspect ratio of rectangles (see **good** rectangle).

Formulas to evaluate side lengths and aspect ratio are given in the section 2.

## 2 Calculations

### 2.1 Length of $\Delta_1$ or $\Delta_2$

Let's fix some terms of continued fraction  $[0; q_1, q_2, q_3, \dots, q_n]$ .  
We will often need to measure difference

$$[0; q_1, q_2, q_3, \dots, q_n, \frac{1}{\Theta_R}] - [0; q_1, q_2, q_3, \dots, q_n, \frac{1}{\Theta_L}],$$

where  $\Theta$ 's are some continuations of the continued fraction.

They generally look like  $\Theta = [0; 12\overline{13}]$  or something<sup>1</sup>. We will set  $\Theta$ 's explicitly.

For the general proof,  $\Theta$ 's will be taken from Table 8.

**Designation.** For given continuation  $\Theta_i$ , denote by  $\varepsilon_i$  the resulting continued fraction:

$$\varepsilon_i = [0; q_1, q_2, \dots, q_n, \frac{1}{\Theta_i}]. \quad (4)$$

Then the following equality takes place:

$$|\varepsilon_i - \varepsilon_j| = \frac{|\Theta_i - \Theta_j|}{Q_n^2 (1 + pQ_i) (1 + pQ_j)}, \quad (5)$$

where

$$p = \frac{Q_{n-1}}{Q_n}.$$

### 2.2 Rectangle aspect ratio

Consider some fixed center of rectangle  $\{a_{i_1} \dots a_{i_2}\}$ .

We will often extend it from the left (right) using continuations  $\Theta_{\gamma_1}, \Theta_{\gamma_2}$  ( $\Theta_{\delta_1}, \Theta_{\delta_2}$ ).

Rule (4) produces  $\gamma_1, \gamma_2$  ( $\delta_1, \delta_2$ ).

Finite continued fractions  $\frac{P_{i_1}}{Q_{i_1}} = [0; a_{-1}, a_{-2}, \dots, a_{i_1}]$  ( $\frac{P_{i_2}}{Q_{i_2}} = [0; a_1, a_2, \dots, a_{i_2}]$ ) are their convergents.

Then

$$\left| \frac{\gamma_1 - \gamma_2}{\delta_1 - \delta_2} \right| = \frac{1}{q} \left| \frac{\Theta_{\gamma_1} - \Theta_{\gamma_2}}{\Theta_{\delta_1} - \Theta_{\delta_2}} \right| \frac{1 + p'\Theta_{\delta_1}}{1 + p\Theta_{\gamma_1}} \frac{1 + p'\Theta_{\delta_2}}{1 + p\Theta_{\gamma_2}} \approx \frac{1}{q} \left| \frac{\Theta_{\gamma_1} - \Theta_{\gamma_2}}{\Theta_{\delta_1} - \Theta_{\delta_2}} \right|, \quad (6)$$

where

$$p = \frac{Q_{i_1+1}}{Q_{i_1}}, \quad p' = \frac{Q_{i_2-1}}{Q_{i_2}}, \quad q = \frac{Q_{i_1}^2}{Q_{i_2}^2}.$$

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<sup>1</sup>Here, as always in this book,  $\overline{abc}^k$  means  $k$ -times repetition of  $abc$ , and  $\overline{abc}$  means infinite repetition.

### 3 Rectangle boundaries

We will set boundaries for rectangles in a different way.

To distinguish rectangles, we will introduce the notion of left- or right-shortened rectangles.

It is given in subsections 3.1-3.3.

Subsections 3.4-3.5 provide the rules for boundaries  $\Delta'_1, \Delta''_1, \Delta'_2, \Delta''_2$ .

#### 3.1 Resection

**Definition.** Call **resection** of a segment  $A = [a; b]$  a process of removing subsegment  $A_{12} = [a_1; b_1]$ , leaving two segments  $A_1 \sqcup A_2 = [a; a_1] \sqcup [b_1; b]$ .

**Definition.** Call subsegment  $A_{12} \subset A$  **normal**, if it is thicker than the two remaining subsegments:

$$|A_{12}| \leq \min \{|A_1|, |A_2|\} \quad (7)$$

We call a resection **normal** if the resected subsegment is normal.

**Proposition.** For any normal resection, having

$$A + A = (A_1 \sqcup A_2) + (A_1 \sqcup A_2). \quad (8)$$

#### 3.2 Shortened rectangle

Consider a horizontal rectangle  $\Delta$ .

##### 3.2.1 Case $i_1 \equiv i_2 \equiv 0 \pmod{2}$

If both  $i_1$  and  $i_2$  are even, then left- and right-shortened rectangles are defined as follows.

**Definition.** Rectangle  $\Delta$  is called left-shortened, if for subrectangle  $\{3, 3\}$  the following condition takes place:

$$|\Delta_1(3)| \leq 1.4 \cdot |\Delta_2(3)|. \quad (9)$$

Here, as in (3), we allow terms  $a_s$  for  $s < i_1$  and  $s > i_2$  to be integers  $\{1, 2, 3\}$ , so (9) can be rewritten as

$$|[0; a_{-1}, \dots, a_{i_1}, 3, \overline{3}, \overline{1}] - [0; a_{-1}, \dots, a_{i_1}, \overline{3}, \overline{1}]| \leq |[0; a_1, \dots, a_{i_2}, 3, \overline{3}, \overline{1}] - [0; a_1, \dots, a_{i_2}, \overline{3}, \overline{1}]|.$$

For further convenience, we also introduce the opposite to (9) condition:

**Definition.** Rectangle  $\Delta$  is called left-normal, if

$$|\Delta_1(3)| > 1.4 \cdot |\Delta_2(3)|. \quad (10)$$

Now we introduce the notion of right-shortened rectangle:

**Definition.** Rectangle  $\Delta$  is called right-shortened, if for subrectangle  $\{31, 13\}$  the following condition takes place:

$$|\Delta_1(13)| \leq 1.4 \cdot |\Delta_2(13)|. \quad (11)$$

As in 3.2.1, we allow terms  $a_s$  for  $s < i_1$  and  $s > i_2$  to be integers  $\{1, 2, 3\}$ , so (11) can be rewritten as

$$|[0; a_{-1}, \dots, a_{i_1}, 1, 3, \overline{3, 1}] - [0; a_{-1}, \dots, a_{i_1}, \overline{1, 3}]| \leq |[0; a_1, \dots, a_{i_2}, 1, 3, \overline{3, 1}] - [0; a_1, \dots, a_{i_2}, \overline{1, 3}]|.$$

We also introduce the opposite condition:

**Definition.** Rectangle  $\Delta$  is called right-normal, if

$$|\Delta_1(13)| > 1.4 \cdot |\Delta_2(13)|. \quad (12)$$

### 3.2.2 Other cases

If  $i_1 \equiv i_2 \pmod{2}$  and  $i_1$  is odd, then the conditions for left- and right-shortened rectangles are swapped.

In case  $i_1 \not\equiv i_2 \pmod{2}$ , the notions of left- and right-shortened rectangles are inferred from subrectangles  $\{1, \}$ ,  $\{2, \}$ , and  $\{3, \}$ .

We will refer to the relevant conditions from 3.5

## 3.3 Explanation of shortened

Notion left-shortened is used to set the lower bound  $\Delta'$  for rectangle  $\Delta$ .

Notion right-shortened is used to set the upper bound  $\Delta''$ .

For example, when interested in  $\Delta'$  when  $i_1$  is even and  $i_2$  is odd, one has to consider larger  $a_{i_1-1}$  and smaller  $a_{i_2+1}$ . As the rectangle is horizontal, we will add terms to the left first. So we will check the condition (11) for  $\{2, \}$  or  $\{3, \}$ .

In other words, check whether  $\{2, \}$  or  $\{3, \}$  is left-shortened or left-normal (recall that  $i_1 - 1$  and  $i_2$  are odd, so left-shortenence is defined by (11)).

Which subrectangle ( $\{2, \}$  or  $\{3, \}$ ) to take, however, depends on terms  $a_{i_1+1}$  and  $a_{i_1}$  (see 3.4).

## 3.4 How we ensure centeredness

Consider integers  $q_1, q_2, \dots, q_n$ . Let  $\{\delta_n\}$  be the set of fractions  $\delta_n = [0; q_1, q_2, \dots, q_n, \dots]$  with  $n$  fixed terms. We will suppose that  $n$  is even (for odd  $n$  the bounds are swapped).

At first, determine the smallest of fractions  $\delta_n$ .

We will consider 2 cases:  $S$  (Shortened) and  $N$  (Normal):

$$S. \quad q_{n-1} = 3, q_n = 1. \quad (13a)$$

$$N. \quad \text{Otherwise.} \quad (13b)$$

The lower bound  $\delta'_n$  for segment, containing  $\delta_n$ , is defined by:

$$\begin{aligned} S. \quad & \delta'_n = [0; q_1, \dots, q_n, 213\overline{12}]. \\ N. \quad & \delta'_n = [0; q_1, \dots, q_n, 3\overline{12}]. \end{aligned}$$

To set the upper bound  $\delta''_n$ , largest of  $\delta_n$ , consider 2 other cases:

$$S. \quad q_n = 3. \quad (14a)$$

$$N. \quad q_n \neq 3. \quad (14b)$$

Then

$$\begin{aligned} S. \quad & \delta_n'' = [0; q_1, \dots, q_n, 1213\overline{12}]. \\ N. \quad & \delta_n'' = [0; q_1, \dots, q_n, 13\overline{12}]. \end{aligned}$$

These bounds will allow us to construct sequences  $\mathcal{M}$ , for which combination (31313) is forbidden and, therefore, the following condition takes place:

$$f_i(\mathcal{M}) \leq \lambda(\overline{31312}) \approx 4,5241, \quad i \neq 0,$$

which will ensure (1).

### 3.5 Formal

Let's now turn to concrete definitions and bounds. Remind that we are looking at the horizontal rectangle  $\Delta$ .

Suppose that  $i_1 \equiv i_2 \pmod{2}$ ,  $i_1$  is even. (If  $i_1$  is odd, then  $\Delta'$  and  $\Delta''$  are swapped.)

#### 3.5.1 Bounds for $\Delta'$

- I. Suppose both  $\{\gamma_0(\mathcal{M})\}$  and  $\{\delta_0(\mathcal{M})\}$  satisfy (13b) and the rectangle  $\Delta$  is left-normal, that is, satisfies (10). We will denote such situation by  $N - N - N$  (segment  $\Delta_1$  is left-normal,  $\Delta_2$  is left-normal, rectangle  $\Delta$  is normal).

In this case define  $\Delta'$  by equation

$$\Delta' = f(\overline{21}3a_{i_1} \dots a_{i_2} 3\overline{12}). \quad (15)$$

- IIa. Sets  $\{\gamma_0(\mathcal{M})\}$  and  $\{\delta_0(\mathcal{M})\}$  meet condition (13b) and  $\Delta$  is left-shortened, that is, meets condition (9). This is case  $N - N - S$  (segments  $\Delta_1$  and  $\Delta_2$  are left-normal, rectangle  $\Delta$  is left-shortened).

Then

$$\Delta' = f(\overline{21}3a_{i_1} \dots a_{i_2} 213\overline{12}). \quad (16)$$

- IIb. Set  $\{\gamma_0(\mathcal{M})\}$  meets (13b),  $\{\delta_0(\mathcal{M})\}$  meets (13a). No matter which condition (9) of (10) is met. It is the case  $N - S$  (segment  $\Delta_1$  is left-normal, segment  $\Delta_2$  left-shortened). Bound  $\Delta'$  is defined by (16).

- III. Set  $\{\gamma_0(\mathcal{M})\}$  meets (13a),  $\{\delta_0(\mathcal{M})\}$  meets (13b). In this  $S - N$  case (segment  $\Delta_1$  is left-shortened, segment  $\Delta_2$  is left-normal)  $\Delta'$  is defined as follows:

$$\Delta' = f(\overline{21}312a_{i_1} \dots a_{i_2} 3\overline{12}). \quad (17)$$

- IV. Both  $\{\gamma_0(\mathcal{M})\}$  and  $\{\delta_0(\mathcal{M})\}$  meet (13a). In this  $S - S$  case (both segments  $\Delta_1$  and  $\Delta_2$  are left-shortened)  $\Delta'$  is defined by

$$\Delta' = f(\overline{21}312a_{i_1} \dots a_{i_2} 213\overline{12}). \quad (18)$$

Left side of the figure 1 illustrates these bounds.



Figure 1: Bounds  $\Delta'$  (left) and  $\Delta''$  (right).

Hatched areas correspond to values of  $a_{i_1-1}$  and  $a_{i_2+1}$  (on the left) or  $a_{i_1-2}$  and  $a_{i_2+2}$  (on the right), equal to 3, which can not appear in the concrete case.

$$\Delta'_1 = \gamma(\Theta_i), i = 3, 30, \Delta'_2 = \delta(\Theta_i), i = 3, 30, \Delta' = \Delta'_1 + \Delta'_2.$$

$$\Delta''_1 = \gamma(\Theta_i), i = 90, 94, \Delta''_2 = \delta(\Theta_i), i = 90, 94.$$

### 3.5.2 Bounds for $\Delta''$

Now we will provide formulas for  $\Delta''$ :

$$I \quad \Delta'' = f(\overline{2131}a_{i_1}\dots a_{i_2}13\overline{12}), \quad (19a)$$

$$II \quad \Delta'' = f(\overline{2131}a_{i_1}\dots a_{i_2}1213\overline{12}), \quad (19b)$$

$$III \quad \Delta'' = f(\overline{213121}a_{i_1}\dots a_{i_2}13\overline{12}), \quad (19c)$$

$$IV \quad \Delta'' = f(\overline{213121}a_{i_1}\dots a_{i_2}1213\overline{12}). \quad (19d)$$

Figure (2) regulates the choice of the formulas.

Case	$\Delta''_1$	$\Delta''_2$	Rectangle	$\Delta''$
I	(14b)	(14b)	(12) $N - N - N$	(19a)
IIa	(14b)	(14b)	(11) $N - N - S$	(19b)
IIb	(14b)	(14a)	$N - S$	(19b)
III	(14a)	(14b)	$S - N$	(19c)
IV	(14a)	(14a)	$S - S$	(19d)

Figure 2: Rules for choice of  $\Delta''$  in case  $i_1 \equiv i_2 \pmod{2}$ .

Again, these bounds are illustrated on the right side of the figure 1.

### 3.5.3 Case $i_1 \not\equiv i_2 \pmod{2}$

Now consider case  $i_1 \not\equiv i_2 \pmod{2}$ ,  $i_1$  is even. We will use rules from figure (3) to choose one of 4 formulas for  $\Delta'$ .

$$I \quad \Delta' = f(\overline{213}a_{i_1}\dots a_{i_2}13\overline{12}), \quad (20a)$$

$$II \quad \Delta' = f(\overline{213}a_{i_1}\dots a_{i_2}1213\overline{12}), \quad (20b)$$

$$III \quad \Delta' = f(\overline{21312}a_{i_1}\dots a_{i_2}13\overline{12}), \quad (20c)$$

$$IV \quad \Delta' = f(\overline{21312}a_{i_1}\dots a_{i_2}1213\overline{12}). \quad (20d)$$

Case	$\Delta''_1$	$\Delta''_2$	Case name	$\Delta''$
I	(13b)	(14b)	$N - N$	(20a)
II	(13b)	(14a)	$N - S$	(20b)
III	(13a)	(14b)	$S - N$	(19c)
IV	(13a)	(14a)	$S - S$	(19d)

Figure 3: Rules for choice of  $\Delta'$  in case  $i_1 \not\equiv i_2 \pmod{2}$ ,  $i_1$  is even.

To determine the bound  $\Delta''$ , we will use subrectangle

$$\{1, 0\}.$$

Having  $i_1 - 1 \equiv i_2 \pmod{2}$ , so we can use all the previous formulas to determine  $\Delta''$ .



## 4 Good rectangle

### 4.1 Definition

Consider a horizontal rectangle  $\Delta = \{a_{i_1} \dots a_{i_2}\}$ .

**Definition.** Rectangle  $\Delta$  is called **good**, if subrectangles  $\{2, 0\}$  and  $\{1, 0\}$  intersect.



Figure 4: Good rectangles if  $i_1$  is odd (upper) and even (lower).

For example, in case  $i_1$  is even, goodness is equivalent to

$$\{2, 0\}'' \geq \{1, 0\}'. \quad (21)$$

Bounds of rectangles are determined by the rules from section 3.

If the rectangle  $\Delta$  is not good (for example, (21) doesn't take place), then

$$(\{2, 0\}''; \{1, 0\}') \not\subset \Delta.$$

Clearly, if the rectangle is not good, then one can not split it into smaller subrectangles whose projections cover the projection of initial one. That's why we will only consider good rectangles during the proof.

### 4.2 Sufficient conditions of goodness

#### 4.2.1 Results

A horizontal rectangle  $\Delta$  is good, if

$$\frac{\Delta_1}{\Delta_2} < \begin{cases} 3.8, & i_1 \equiv i_2 \pmod{2}, \quad \{\delta(\mathcal{M})\} \text{ meets (13b),} \\ 3.43, & i_1 \not\equiv i_2 \pmod{2}, \quad \{\delta(\mathcal{M})\} \text{ meets (13b),} \\ 2.9, & \text{otherwise.} \end{cases} \quad (22)$$

### 4.2.2 Universal 2, 9 bound

We will introduce a sufficient conditions for a rectangle to be good.

**Designation.** For given continuations  $\Theta_\gamma$  and  $\Theta_\delta$ , denote by  $\gamma$  and  $\delta$  the resulting continued fractions:

$$\gamma = [0; a_{-1}, \dots, a_{i_1}, \frac{1}{\Theta_\gamma}],$$

$$\delta = [0; a_1, \dots, a_{i_2}, \frac{1}{\Theta_\delta}].$$

As stated in 1.1,  $\gamma$ 's correspond to the lhs of  $\mathcal{M}$ , and  $\delta$ 's correspond to the rhs of  $\mathcal{M}$ . Variables  $\Theta$  will be taken from the Figure 8 and will be specified in each case separately.

Suppose that  $i_1$  is even.

Remind that  $|\Delta_1| \geq |\Delta_2|$ , which means that

$$\frac{|\gamma'' - \gamma'|}{|\delta'' - \delta'|} \geq 1,$$

where

$$\Theta_{\gamma'} = \Theta_{\delta'} = \Theta_1, \quad \Theta_{\gamma''} = \Theta_{\delta''} = \Theta_{95}.$$

Using (6), rewrite it as

$$q \frac{1 + p\Theta_1}{1 + p'\Theta_1} \frac{1 + p\Theta_{95}}{1 + p'\Theta_{95}} \leq 1.$$

Goodness can be written as

$$\gamma' - \gamma'' < |\delta' - \delta''|, \tag{23}$$

where  $\gamma' = \Delta_1(1)'$  and  $\gamma'' = \Delta_1(2)''$ .

For an arbitrary rectangle  $\Delta$ , taking

$$\Theta_{\gamma'} = \Theta_{66}, \quad \Theta_{\gamma''} = \Theta_{63}, \quad \Theta_{\delta'} = \Theta_{90}, \quad \Theta_{\delta''} = \Theta_{30}.$$

Inequality (23) transforms into

$$0, 313 < q \frac{1 + p\Theta_{63}}{1 + p'\Theta_{30}} \frac{1 + p\Theta_{66}}{1 + p'\Theta_{90}}. \tag{24}$$

Suppose that

$$\frac{\Delta_1}{\Delta_2} < 2, 9, \tag{25}$$

which is equivalent to

$$\frac{1}{q} \frac{1 + p'\Theta_1}{1 + p\Theta_1} \frac{1 + p'\Theta_{95}}{1 + p\Theta_{95}} < 2, 9. \tag{26}$$

Then (24) takes place. Indeed, it is so, if

$$\frac{1}{2, 9} \frac{1 + p'\Theta_1}{1 + p\Theta_1} \frac{1 + p'\Theta_{95}}{1 + p\Theta_{95}} > 0, 313 \frac{1 + p'\Theta_{30}}{1 + p\Theta_{63}} \frac{1 + p'\Theta_{90}}{1 + p\Theta_{66}}.$$

or, equivalent,

$$1, 1 > \frac{1+p\Theta_1}{1+p\Theta_{63}} \frac{1+p\Theta_{95}}{1+p\Theta_{66}} \frac{1+p'\Theta_{30}}{1+p'\Theta_1} \frac{1+p'\Theta_{90}}{1+p'\Theta_{95}},$$

which is checked directly.

Condition (25) is sufficient for rectangle to be good, regardless of the parity of  $i_1$  and  $i_2$  and the left or right shortness or normalness of rectangle.

#### 4.2.3 Case $i_1 \equiv i_2 \pmod{2}$

Now consider case  $i_1 \equiv i_2 \pmod{2}$ .

Suppose that the right hand side  $\{\delta(\mathcal{M})\}$  is left-normal, that is, meets (13b).

Equivalent, the case  $a_{i_2} = 1$ ,  $a_{i_2-1} = 3$  doesn't take place.



This assumption allows us to substitute the following  $\gamma$ 's and  $\delta$ 's into (23):

$$\Theta_{\gamma'} = \Theta_{66}, \Theta_{\gamma''} = \Theta_{63}, \Theta_{\delta'} = \Theta_{90}, \Theta_{\delta''} = \Theta_3.$$

The rhs left-normality leaves us hope that the bound  $\Delta_2''$  will be set to  $\Delta_2(\Theta_3)$ , so we are substituting  $\Theta_{\delta''}$  with  $\Theta_3$  instead of  $\Theta_{30}$ .

Now, instead of (24) we will get

$$0, 253 < q \frac{1+p\Theta_{63}}{1+p'\Theta_3} \frac{1+p\Theta_{66}}{1+p'\Theta_{90}}. \quad (27)$$

Such choice of  $\Theta_{\gamma'}$  and  $\Theta_{\delta''}$  is fine, if the following inequality takes place:

$$\delta' - \delta'' > 1, 4(\gamma' - \gamma''), \quad (28)$$

where

$$\Theta_{\gamma'} = \Theta_{68}, \Theta_{\gamma''} = \Theta_{65}, \Theta_{\delta'} = \Theta_{28}, \Theta_{\delta''} = \Theta_1,$$

so we can rewrite (28) as

$$0, 253 < q \frac{1+p\Theta_{65}}{1+p'\Theta_1} \frac{1+p\Theta_{68}}{1+p'\Theta_{28}}. \quad (29)$$

We can notice that (29) follows from (27). Indeed, that follows from the inequality

$$0, 253 \frac{1+p'\Theta_3}{1+p'\Theta_{63}} \frac{1+p\Theta_{90}}{1+p\Theta_{66}} > 0, 269 \frac{1+p'\Theta_1}{1+p'\Theta_{65}} \frac{1+p\Theta_{28}}{1+p\Theta_{68}},$$

or inequality

$$\frac{1+p\Theta_{65}}{1+p\Theta_{63}} \frac{1+p\Theta_{68}}{1+p\Theta_{66}} \frac{1+p'\Theta_3}{1+p'\Theta_1} \frac{1+p'\Theta_{90}}{1+p'\Theta_{28}} > 1, 064.$$

Overall, we have proved that (27) is enough for rectangle to be good.

Suppose that

$$\frac{\Delta_1}{\Delta_2} < 3, 8, \quad (30)$$

or

$$\frac{1}{q} \frac{1 + p'\Theta_1}{1 + p\Theta_1} \frac{1 + p'\Theta_{95}}{1 + p\Theta_{95}} < 3, 8.$$

Then (27) takes place. Indeed, it is so, if

$$\frac{1}{3, 8} \frac{1 + p'\Theta_1}{1 + p\Theta_1} \frac{1 + p'\Theta_{95}}{1 + p\Theta_{95}} > 0, 253 \frac{1 + p'\Theta_3}{1 + p'\Theta_{63}} \frac{1 + p\Theta_{90}}{1 + p\Theta_{66}}.$$

The last inequality is transformed into

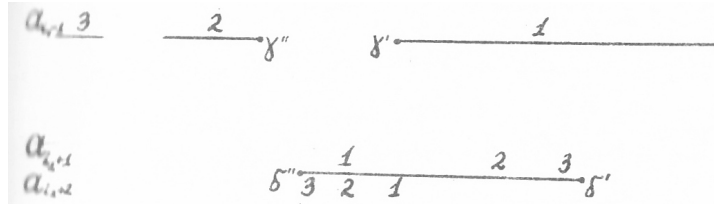
$$1, 04 > \frac{1 + p'\Theta_3}{1 + p'\Theta_1} \frac{1 + p'\Theta_{90}}{1 + p'\Theta_{95}} \frac{1 + p\Theta_1}{1 + p\Theta_{63}} \frac{1 + p\Theta_{95}}{1 + p\Theta_{66}},$$

which is easily checked.

#### 4.2.4 Case $i_1 \not\equiv i_2 \pmod{2}$

Now consider case  $i_1 \not\equiv i_2 \pmod{2}$  and, again, the right hand side  $\{\delta(\mathcal{M})\}$  is left-normal, in other words, case  $a_{i_2} = 1$ ,  $a_{i_2-1} = 3$  doesn't take place.

Suppose that  $i_1$  is even.



Substituting

$$\Theta_{\gamma'} = \Theta_{66}, \quad \Theta_{\gamma''} = \Theta_{59}, \quad \Theta_{\delta'} = \Theta_3, \quad \Theta_{\delta''} = \Theta_{90}$$

into (23), obtain

$$0, 2885 < q \frac{1 + p\Theta_{59}}{1 + p'\Theta_3} \frac{1 + p\Theta_{66}}{1 + p'\Theta_{90}}. \quad (31)$$

Suppose that

$$\frac{\Delta_1}{\Delta_2} < 3, 43 \quad (32)$$

or

$$\frac{1}{q} \frac{1 + p'\Theta_1}{1 + p\Theta_1} \frac{1 + p'\Theta_{95}}{1 + p\Theta_{95}} < 3, 43.$$

Then (31) takes place. Indeed, it is so, if

$$\frac{1}{3, 43} \frac{1 + p'\Theta_1}{1 + p\Theta_1} \frac{1 + p'\Theta_{95}}{1 + p\Theta_{95}} > 0, 2885 \frac{1 + p'\Theta_3}{1 + p\Theta_{59}} \frac{1 + p'\Theta_{90}}{1 + p\Theta_{66}}.$$

or

$$1,0105 > \frac{1+p'\Theta_3}{1+p'\Theta_1} \frac{1+p'\Theta_{90}}{1+p'\Theta_{95}} \frac{1+p\Theta_1}{1+p\Theta_{59}} \frac{1+p\Theta_{95}}{1+p\Theta_{66}}.$$

Increasing the right part, obtain

$$1,0105 > 0,9896 \frac{1+p \cdot 1,0551 + p^2 \cdot 0,20875}{1+p \cdot 0,983 + p^2 \cdot 0,237},$$

which is easily checked.

## 5 Initial set of rectangles

We present a set of rectangles whose projections cover the segment from the Freiman's constant to  $\sqrt{21}$ . All of them are good. Further sections will present the algorithm of splitting these rectangles into subrectangles correctly.

$$\begin{aligned}
 1) & \quad \{ 3\underset{\circ}{4}3 \} \\
 2) & \quad \{ 3\underset{\circ}{1}3\underset{\circ}{4}3\underset{\circ}{1}2 \} \\
 3) & \quad \{ 1\underset{\circ}{2}3\underset{\circ}{4}4\underset{\circ}{3}1 \} \\
 4) & \quad \{ 3\underset{\circ}{1}3\underset{\circ}{4}3\underset{\circ}{1}3 \} \\
 5) & \quad \{ 2\underset{\circ}{1}1\underset{\circ}{2}3\underset{\circ}{4}4\underset{\circ}{3}2\underset{\circ}{2} \} \\
 6) & \quad \{ 3\underset{\circ}{1}1\underset{\circ}{2}3\underset{\circ}{4}4\underset{\circ}{3}2\underset{\circ}{3} \} \\
 7) & \quad \{ 3\underset{\circ}{1}1\underset{\circ}{2}3\underset{\circ}{4}4\underset{\circ}{3}2\underset{\circ}{2} \} \\
 8+2n, \kappa) & \quad \{ \overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{2}\overset{\kappa}{1}\overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{1}\overset{\kappa}{2}3\underset{\circ}{4}4\underset{\circ}{3}2\underset{\circ}{2}3\overset{\kappa}{1}\overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{2}\overset{\kappa}{1}\overset{\kappa}{3} \} \quad (I3.1) \\
 9+2n, \kappa) & \quad \{ \overset{\kappa-1}{3}\overset{\kappa-1}{2}\overset{\kappa-1}{1}3\overset{\kappa-1}{1}\overset{\kappa-1}{3}\overset{\kappa-1}{1}\overset{\kappa-1}{2}\overset{\kappa-1}{3}\overset{\kappa-1}{1}\overset{\kappa-1}{1}\overset{\kappa-1}{2}3\underset{\circ}{4}4\underset{\circ}{3}2\underset{\circ}{2}3\overset{\kappa}{1}\overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{2}\overset{\kappa}{1}\overset{\kappa}{3} \} \quad (I3.2) \\
 9+2n, \kappa, \rho) & \quad \{ \overset{\rho}{3}\overset{\rho}{1}\overset{\rho}{3}\overset{\rho}{1}\overset{\rho}{2}\overset{\rho}{1}\overset{\rho}{3}\overset{\rho}{1}\overset{\rho}{3}\overset{\rho}{1}\overset{\rho}{1}\overset{\rho}{2}3\underset{\circ}{4}4\underset{\circ}{3}2\underset{\circ}{2}3\overset{\kappa}{1}\overset{\kappa}{3}\overset{\kappa}{1}\overset{\kappa}{2}\overset{\kappa}{1}\overset{\kappa}{3}\overset{\rho}{1}\overset{\rho}{2}\overset{\rho}{1}\overset{\rho}{3} \} \quad (I3.3)
 \end{aligned}$$

Figure 5: Initial set of rectangles.

## 6 Induction, $i_1 \not\equiv i_2 \pmod{2}$

Let  $\Delta = \{a_{i_1}, \dots, a_{i_2}\}$  be a horizontal rectangle, satisfying conditions from sections 3 and 4.

This section deals with the case  $i_1 \not\equiv i_2 \pmod{2}$ .

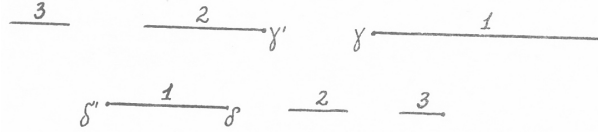
It is easier, because in this case both the lower-left and upper-right corners are filled with the “wide” rectangles  $\{1, \}$  and  $\{, 1\}$  (see figure 6). In case  $i_1 \equiv i_2 \pmod{2}$  the lower-left corner, filled with  $\{3, 3\}$ , will be a pain in the neck.

Without loss of generality, we may assume that  $i_1$  is even and, therefore,  $i_2$  is odd. As the reader will see, the argument is repeated for the opposite parity, up to differences in illustrations.

### 6.1 Case $\{, 1\}$ is good

At first, suppose that the subrectangle  $\{, 1\}$  is good.

It is so, if



$$\gamma - \gamma' < \delta - \delta', \quad (33)$$

where

$$\Theta_\gamma = \Theta_{66}, \quad \Theta_{\gamma'} = \Theta_{63}, \quad \Theta_\delta = \Theta_{70}, \quad \Theta_{\delta'} = \Theta_{90},$$

which can be rewritten with (6) as follows:

$$0,74 < q \frac{1 + p\Theta_{63}}{1 + p'\Theta_{66}} \frac{1 + p\Theta_{70}}{1 + p'\Theta_{90}}. \quad (34)$$

Constants  $\Theta_\gamma$  and  $\Theta_\delta$  are chosen to ensure that

$$[\delta, \delta'] \subset \Delta_2,$$

regardless of the rules from the section 3 defining  $\Delta'_2$  and  $\Delta''_2$ .

From (34) it follows that the original rectangle  $\Delta$  is contained within the union of the subrectangles  $\{1, \}$  and  $\{, 1\}$ .

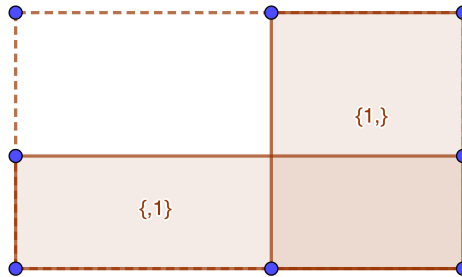


Figure 6: Subrectangles  $\{1, \}$  and  $\{, 1\}$ .

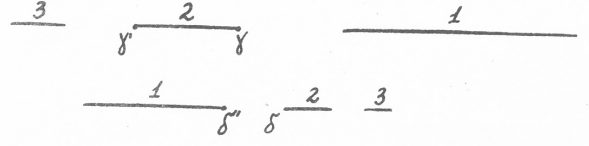
Now we will try contradiction and suppose that

$$0,74 \geq q \frac{1+p\Theta_{63}}{1+p'\Theta_{66}} \frac{1+p\Theta_{70}}{1+p'\Theta_{90}}. \quad (35)$$

We will use the inequality (35) until the end of the section.

## 6.2 Case $\Delta$ is left-shortened

Now suppose that the following inequality takes place:



$$\gamma - \gamma' > \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{63}, \Theta_{\gamma'} = \Theta_{35}, \Theta_\delta = \Theta_{63}, \Theta_{\delta'} = \Theta_{70},$$

which can be rewritten as

$$0,558 > q \frac{1+p\Theta_{35}}{1+p'\Theta_{63}} \frac{1+p\Theta_{63}}{1+p'\Theta_{70}}. \quad (36)$$

If the rectangle  $\Delta$  is of type  $S - S$  or  $S - N$ , that is, the lower bound  $\Delta'$  is defined with (20c) or (20d), then the splitting is finished, as  $\Delta$  is contained within the union of  $\{1, \}$  and  $\{2, \}$ .

## 6.3 Case $\Delta$ is left-normal

Now turn to case if (36) takes place, and  $\Delta$  is of type  $N - S$  or  $N - N$ , so  $\Delta'$  is set with one of the rules (20a) or (20b).

Let's see when the subrectangle  $\{3, 11\}$  is right-normal. The following condition should take place:



$$\gamma - \gamma' > 1,4(\delta - \delta'),$$

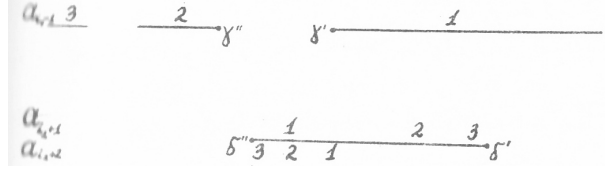
where

$$\Theta_\gamma = \Theta_{28}, \Theta_{\gamma'} = \Theta_{22}, \Theta_\delta = \Theta_{68}, \Theta_{\delta'} = \Theta_{65},$$

which can be written as

$$0,345 > q \frac{1+p\Theta_{22}}{1+p'\Theta_{65}} \frac{1+p\Theta_{28}}{1+p'\Theta_{68}}. \quad (37)$$





If the condition (37) takes place, then the inequality

$$\gamma - \gamma' > \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{25}, \Theta_{\gamma'} = \Theta_3, \Theta_\delta = \Theta_{66}, \Theta_{\delta'} = \Theta_{63},$$

which can be written as

$$0,322 > q \frac{1+p\Theta_3}{1+p'\Theta_{63}} \frac{1+p\Theta_{25}}{1+p'\Theta_{66}}. \quad (38)$$

All in all, if rectangle  $\Delta$  satisfies both conditions (37) and (38), then it can be split into  $\{1, \}$ ,  $\{2, \}$  and  $\{3, \}$ .

Now suppose that at least one of (37) and (38) doesn't take place. We will show that then we can split  $\Delta$  into  $\{1, \}$ ,  $\{2, \}$  and  $\{3, 1\}$ .

First, we need to check goodness of subcovering  $\{3, 1\}$ . We will prove that it meets the sufficient condition (32). We need to show that

$$3,43(\gamma - \gamma') > |\delta - \delta'|, \quad (39)$$

where

$$\Theta_\gamma = \Theta_{28}, \Theta_{\gamma'} = \Theta_1, \Theta_\delta = \Theta_{95}, \Theta_{\delta'} = \Theta_{65}.$$

Inequality (39) is equivalent to

$$0,628 > q \frac{1+p\Theta_1}{1+p'\Theta_{65}} \frac{1+p\Theta_{28}}{1+p'\Theta_{95}}.$$

Recalling (36), we have to show that

$$0,558 \frac{1+p'\Theta_{63}}{1+p\Theta_{35}} \frac{1+p'\Theta_{70}}{1+p\Theta_{63}} < 0,627 \frac{1+p'\Theta_{65}}{1+p\Theta_1} \frac{1+p'\Theta_{95}}{1+p\Theta_{28}},$$

and it is true.

Now show that the subrectangles  $\{3, 1\}$  and  $\{2, 1\}$  intersect.

First, let  $a_{i_2} = 3$ , so  $\Delta'_2$  is set with the formula (20b).

The following inequality should take place:

$$\gamma - \gamma' < \delta - \delta', \quad (40)$$

where

$$\Theta_\gamma = \Theta_{30}, \Theta_{\gamma'} = \Theta_{25}, \Theta_\delta = \Theta_{70}, \Theta_{\delta'} = \Theta_{90},$$

which is transformed into

$$0,328 < q \frac{1+p\Theta_{25}}{1+p'\Theta_{70}} \frac{1+p\Theta_{30}}{1+p'\Theta_{90}}. \quad (41)$$

If (37) doesn't take place, then we need the following inequality for (41):

$$\begin{aligned} 0,345 \frac{1+p'\Theta_{65}}{1+p\Theta_{22}} \frac{1+p'\Theta_{68}}{1+p\Theta_{28}} &> 0,328 \frac{1+p'\Theta_{70}}{1+p\Theta_{25}} \frac{1+p'\Theta_{90}}{1+p\Theta_{30}} \\ &\Downarrow \\ 1,05 &> \frac{1+p'\Theta_{70}}{1+p'\Theta_{65}} \frac{1+p'\Theta_{90}}{1+p'\Theta_{68}} \frac{1+p\Theta_{22}}{1+p\Theta_{25}} \frac{1+p\Theta_{28}}{1+p\Theta_{30}}. \end{aligned}$$

From  $a_{i_2} = 3$  it follows that  $p' \leq \frac{1}{3}$ . Setting  $p' = \frac{1}{3}$  and  $p = \frac{1}{4}$  in the rhs, increasing it and obtaining the correct inequality. Thus, it is correct.

Now suppose that (37) takes place, while (38) doesn't. Setting  $\Theta_\delta = \Theta_{66}$  (instead of  $\Theta_{70}$ ) in (40), get the following inequality:

$$0,288 < q \frac{1+p\Theta_{25}}{1+p'\Theta_{66}} \frac{1+p\Theta_{30}}{1+p'\Theta_{90}}. \quad (42)$$

Inequality (42) follows from denial of inequality (38), if

$$\begin{aligned} 0,322 \frac{1+p'\Theta_{63}}{1+p\Theta_3} \frac{1+p'\Theta_{66}}{1+p\Theta_{25}} &> 0,298 \frac{1+p'\Theta_{66}}{1+p\Theta_{25}} \frac{1+p'\Theta_{90}}{1+p\Theta_{30}} \\ &\Downarrow \\ 1,08 &> \frac{1+p\Theta_3}{1+p\Theta_{30}} \frac{1+p'\Theta_{90}}{1+p'\Theta_{63}}. \end{aligned}$$

Setting  $p = \frac{1}{4}$  and  $p' = \frac{1}{3}$ , easily check the last inequality.

## 6.4 Case we can consider $\{2, 1\}$

Now consider the case, when  $a_{i_2} \neq 3$  and  $\Delta'_1$  is defined with (20a).

For the subrectangle  $\{2, 1\}$  left-normality we need

$$1,4(\gamma - \gamma') < \|\delta - \delta'\|, \quad (43)$$

where

$$\Theta_\gamma = \Theta_{33}, \quad \Theta_{\gamma'} = \Theta_{29}, \quad \Theta_\delta = \Theta_{95}, \quad \Theta_{\delta'} = \Theta_{92},$$

so (43) can be rewritten as

$$0,182 < q \frac{1+p\Theta_{29}}{1+p'\Theta_{92}} \frac{1+p\Theta_{33}}{1+p'\Theta_{95}}. \quad (44)$$

If neither (37) nor (38) takes place, then it's easy to check (44).

In (40) we can set  $\Theta_{\gamma'} = \Theta_{94}$  (instead of  $\Theta_{90}$ ), so (40) is transformed into

$$0,248 < q \frac{1+p\Theta_{25}}{1+p'\Theta_{70}} \frac{1+p\Theta_{30}}{1+p'\Theta_{94}}. \quad (45)$$

If (37) doesn't take place, then for (45) we will check the following:

$$\begin{aligned} 0,345 \frac{1+p'\Theta_{65}}{1+p\Theta_{22}} \frac{1+p'\Theta_{68}}{1+p\Theta_{28}} &> 0,248 \frac{1+p'\Theta_{70}}{1+p\Theta_{25}} \frac{1+p'\Theta_{94}}{1+p\Theta_{30}} \\ &\Downarrow \\ 1,39 &> \frac{1+p'\Theta_{70}}{1+p'\Theta_{65}} \frac{1+p'\Theta_{94}}{1+p'\Theta_{68}} \frac{1+p\Theta_{22}}{1+p\Theta_{25}} \frac{1+p\Theta_{28}}{1+p\Theta_{30}}, \end{aligned}$$

which is clear.

If (38) doesn't take place, then for (45) we will check

$$\begin{aligned} 0,322 \frac{1+p'\Theta_{63}}{1+p\Theta_3} \frac{1+p'\Theta_{66}}{1+p\Theta_{25}} &> 0,248 \frac{1+p'\Theta_{70}}{1+p\Theta_{25}} \frac{1+p'\Theta_{94}}{1+p\Theta_{30}} \\ &\Updownarrow \\ 1,29 &> \frac{1+p\Theta_3}{1+p\Theta_{30}} \frac{1+p'\Theta_{70}}{1+p'\Theta_{63}} \frac{1+p'\Theta_{94}}{1+p'\Theta_{66}}, \end{aligned}$$

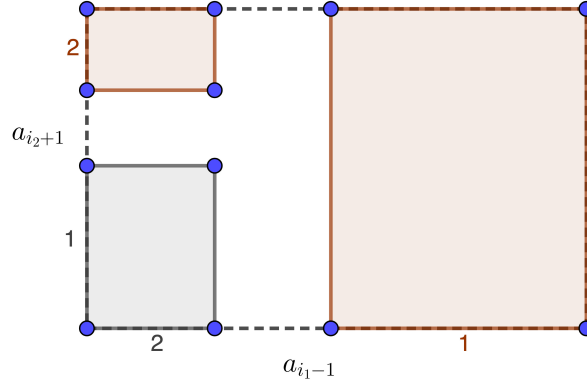
which is true.

## 6.5 Further plan

It remains for us to check the case if (35) takes place and (36) doesn't – instead, having the negation of (36):

$$0,558 \leq q \frac{1+p\Theta_{35}}{1+p'\Theta_{63}} \frac{1+p\Theta_{63}}{1+p'\Theta_{70}}. \quad (46)$$

We have proved that we can consider subrectangles  $\{1, \}$  and  $\{2, 2\}$ .



The picture illustrates the case when the boundaries  $\Delta'_1$  and  $\Delta''_2$  of segments  $\Delta_1$  and  $\Delta_2$  are defined with constants  $\Theta_{\Delta'_1} = \Theta_{\Delta''_2} = \Theta_{30} = [0; 213\overline{12}]$ . In this case, having, in particular,  $a_{i_1} = 1$ ,  $a_{i_1+1} = 3$ . We set segment  $\Delta_1$  to be left-shortened to forbid  $a_{i_1-1} = 3$ , because it can happen that we will face the forbidden combination (31313).

So, in the illustrated case, the only unused subrectangle is  $\{2, 1\}$ . However, subrectangles  $\{2, 1\}$  and  $\{2, 2\}$  doesn't intersect, so we will be unable to construct a family of subrectangles, covering  $\Delta$ .

How to overcome this difficulty? The idea being developed is to use  $a_{i_1-1} = 3$  (and  $a_{i_2+1} = 3$ ), but set  $a_{i_1-2}$ ,  $a_{i_1-3}$  (and  $a_{i_2+2}$ ,  $a_{i_2+3}$ ), which produce the thinner subrectangles and doesn't occur in string (31313).

## 6.6 List of subrectangles

Let's turn to formal plan.

If  $\Delta'_1$  and  $\Delta''_2$  were set with  $\Theta_3 = [0; 31\overline{2}]$ , then we would have been able to take  $\{3, 3\}$ , which intersects with  $\{2, 2\}$ .

Instead of  $\{3, 3\}$ , we will take the following list of subrectangles:

$$\begin{aligned} &\{23, 32\}, \{23, 33\} \text{ (or } \{223, 33\} \text{ and } \{323, 33\}), \{113, 311\}, \\ &\{213, 312\}, \{213, 311\}, \{113, 32\}, \{113, 33\} \text{ (or } \{1113, 33\}), \{213, 33\}. \end{aligned}$$

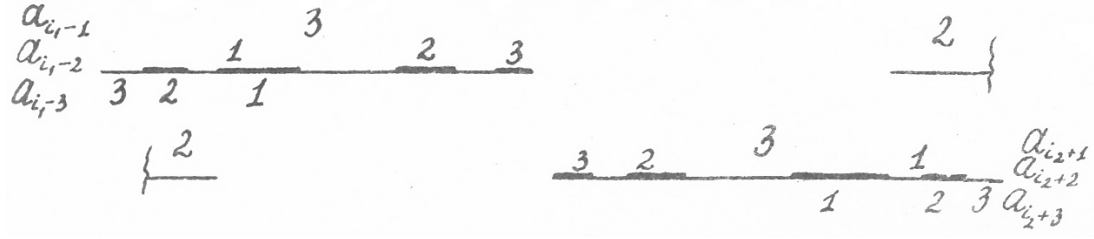


Figure 7: Illustration of the subrectangles replacing the subrectangle  $\{3, 3\}$ .  
I will make a 2d illustration in the future.

The next subrectangle to consider is  $\{3, 2\}$ , but instead we will consider the following subrectangles:

$$\{33, 213\}, \{33, 212\}, \{23, 213\}, \{23, 212\}, \{23, 211\}.$$

## 6.7 Correctness proof

We will show that the projections of adjacent subrectangles intersect and all of them are good.

Show that  $\{23, 32\}$  is good. Indeed, the condition

$$\gamma - \gamma' < 3, 43(\delta - \delta'),$$

where

$$\Theta_\gamma = \Theta_{21}, \Theta_{\gamma'} = \Theta_{15}, \Theta_\delta = \Theta_{15}, \Theta_{\delta'} = \Theta_{21},$$

is equivalent to

$$0, 3 < q \frac{1 + p\Theta_{15}}{1 + p'\Theta_{15}} \frac{1 + p\Theta_{21}}{1 + p'\Theta_{21}}$$

and follows from (46).

Subrectangle  $\{23, 32\}$  intersects with  $\{2, 2\}$ . The following inequality is required:

$$\gamma - \gamma' < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{30}, \Theta_{\gamma'} = \Theta_{19}, \Theta_\delta = \Theta_{16}, \Theta_{\delta'} = \Theta_{59},$$

so obtain condition

$$0, 4612 < q \frac{1 + p\Theta_{19}}{1 + p'\Theta_{16}} \frac{1 + p\Theta_{30}}{1 + p'\Theta_{59}},$$

which follows from 15:

$$\begin{aligned} 0, 558 \frac{1 + p'\Theta_{63}}{1 + p\Theta_{35}} \frac{1 + p'\Theta_{70}}{1 + p\Theta_{63}} &> 0, 4612 \frac{1 + p'\Theta_{16}}{1 + p\Theta_{19}} \frac{1 + p'\Theta_{59}}{1 + p\Theta_{30}} \\ &\Downarrow \\ 1, 2 &> \frac{1 + p'\Theta_{16}}{1 + p'\Theta_{63}} \frac{1 + p'\Theta_{59}}{1 + p'\Theta_{70}} \frac{1 + p\Theta_{35}}{1 + p\Theta_{19}} \frac{1 + p\Theta_{63}}{1 + p\Theta_{30}}, \end{aligned}$$

and the last line is obvious.

Checking the goodness of  $\{23, 33\}$ . The condition

$$\gamma - \gamma' < 3, 43(\delta - \delta')$$

should take place for

$$\Theta_\gamma = \Theta_{21}, \Theta_{\gamma'} = \Theta_{15}, \Theta_\delta = \Theta_{22}, \Theta_{\delta'} = \Theta_{28},$$

and it can be rewritten as follows:

$$0,533 < q \frac{1+p\Theta_{15}}{1+p'\Theta_{22}} \frac{1+p\Theta_{21}}{1+p'\Theta_{28}}. \quad (47)$$

If (47) takes place, then we take  $\{23, 33\}$ . Checking that  $\{23, 33\}$  intersects with  $\{23, 32\}$  is easy. If (47) doesn't take place, then we take  $\{223, 33\}$  and  $\{323, 33\}$  instead.

At first, showing that  $\{223, 33\}$  and  $\{23, 32\}$  intersect.

Subrectangle  $\{223, 33\}$  is right-normal, since

$$1,4(\gamma - \gamma' < \delta - \delta'),$$

where

$$\begin{aligned} \Theta_\gamma &= [0; 3223\overline{1}] = 0,293294, \\ \Theta_{\gamma'} &= [0; 3223\overline{31}] = 0,293176, \\ \Theta_\delta &= \Theta_{22}, \\ \Theta_{\delta'} &= [0; 3333\overline{1}] = 0,302806, \end{aligned}$$

transforms into

$$0,457 < q \frac{1+p\Theta_\gamma}{1+p'\Theta_\delta} \frac{1+p\Theta_{\gamma'}}{1+p'\Theta_{\delta'}},$$

and it follows from (46), if

$$1,22 > \frac{1+p'\Theta_\delta}{1+p'\Theta_{63}} \frac{1+p'\Theta_{\delta'}}{1+p'\Theta_{70}} \frac{1+p\Theta_{35}}{1+p\Theta_\gamma} \frac{1+p\Theta_{63}}{1+p\Theta_{\gamma'}},$$

which is clear.

Now the condition

$$\gamma - \gamma' > \delta - \delta',$$

where

$$\Theta_\gamma = [0; 3223\overline{12}] = 0,293283, \Theta_{\gamma'} = \Theta_{16}, \Theta_\delta = \Theta_{20}, \Theta_{\delta'} = \Theta_{23},$$

transforms into

$$0,561 > q \frac{1+p\Theta_{16}}{1+p'\Theta_{20}} \frac{1+p\Theta_\gamma}{1+p'\Theta_{23}},$$

and it follows from negation of (47).

Let's try to take next subrectangle  $\{113, 32\}$ . Let's see if it intersects with  $\{23, 33\}$  (or  $\{323, 33\}$ ). The condition of intersection

$$\gamma - \gamma' < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{16}, \Theta_{\gamma'} = \Theta_{13}, \Theta_\delta = \Theta_{18}, \Theta_{\delta'} = \Theta_{25},$$

is equivalent to

$$0,7 < q \frac{1+p\Theta_{13}}{1+p'\Theta_{18}} \frac{1+p\Theta_{16}}{1+p'\Theta_{25}}. \quad (48)$$

Assume that (48) doesn't take place:

$$0, 7 \geq q \frac{1 + p\Theta_{13}}{1 + p'\Theta_{18}} \frac{1 + p\Theta_{16}}{1 + p'\Theta_{25}}. \quad (49)$$

Consider subrectangle  $\{113, 311\}$  and show that it intersects with  $\{23, 33\}$ . The following inequality should take place:

$$\gamma - \gamma' < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{16}, \Theta_{\gamma'} = \Theta_{13}, \Theta_\delta = \Theta_{10}, \Theta_{\delta'} = \Theta_{25},$$

Obtain

$$0, 314 < q \frac{1 + p\Theta_{13}}{1 + p'\Theta_{10}} \frac{1 + p\Theta_{16}}{1 + p'\Theta_{25}},$$

which follows from (46).

Now let's show that  $\{213, 312\}$  intersects with  $\{113, 311\}$ .

The condition

$$\gamma - \gamma' < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_8, \Theta_{\gamma'} = \Theta_5, \Theta_\delta = \Theta_3, \Theta_{\delta'} = \Theta_{11},$$

expands to

$$0, 338 < q \frac{1 + p\Theta_3}{1 + p'\Theta_3} \frac{1 + p\Theta_8}{1 + p'\Theta_{11}},$$

and follows from (46).

Show that  $\{213, 311\}$  intersects with  $\{213, 312\}$ . The condition

$$\gamma - \gamma' > \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_5, \Theta_{\gamma'} = \Theta_3, \Theta_\delta = \Theta_5, \Theta_{\delta'} = \Theta_8,$$

transforms into

$$0, 77 > q \frac{1 + p\Theta_3}{1 + p'\Theta_5} \frac{1 + p\Theta_5}{1 + p'\Theta_8}. \quad (50)$$

Inequality (50) follows from (49), because

$$\begin{aligned} 0, 7 \frac{1 + p'\Theta_{18}}{1 + p\Theta_{13}} \frac{1 + p'\Theta_{25}}{1 + p\Theta_{16}} &< 0, 77 \frac{1 + p'\Theta_5}{1 + p\Theta_3} \frac{1 + p'\Theta_8}{1 + p\Theta_5} \\ &\Downarrow \\ \frac{1 + p'\Theta_{18}}{1 + p'\Theta_5} \frac{1 + p'\Theta_{25}}{1 + p'\Theta_8} \frac{1 + p\Theta_3}{1 + p\Theta_{13}} \frac{1 + p\Theta_5}{1 + p\Theta_{16}} &< 1, 1. \end{aligned}$$

Constant  $\Theta_{\delta'}$  can be set to  $\Theta_8$ , only if  $\{213, 311\}$  is right-normal, for which the condition

$$\gamma - \gamma' > 1, 4(\delta - \delta'),$$

where

$$\Theta_\gamma = \Theta_9, \Theta_{\gamma'} = \Theta_7, \Theta_\delta = \Theta_4, \Theta_{\delta'} = \Theta_6,$$

should take place. It is equivalent to

$$0, 8 > q \frac{1 + p\Theta_7}{1 + p'\Theta_4} \frac{1 + p\Theta_9}{1 + p'\Theta_6},$$

which is true in consideration of (49).

Finally, it is very easy to check that  $\{113, 32\}$  intersects with  $\{213, 311\}$ .

Overall, regardless of whether condition 17 is satisfied or not, we come to subrectangle  $\{113, 32\}$ . Further we note that it intersects with  $\{113, 33\}$ . We will check here that the latter one is good. The following inequality is required:

$$\gamma - \gamma' < 3, 8(\delta - \delta'),$$

where

$$\Theta_\gamma = \Theta_{14}, \Theta_{\gamma'} = \Theta_7, \Theta_\delta = \Theta_{22}, \Theta_{\delta'} = \Theta_{28},$$

and obtain

$$0, 44 < q \frac{1 + p\Theta_7}{1 + p'\Theta_{22}} \frac{1 + p\Theta_{14}}{1 + p'\Theta_{28}},$$

which follows from (46).

It is easily checked that  $\{113, 33\}$  intersects with  $\{213, 32\}$ .

Let's find the condition for the subrectangle  $\{2, 11\}$  to be right-normal.

$$\gamma - \gamma' > 1, 4(\delta - \delta'),$$

where

$$\Theta_\gamma = \Theta_{64}, \Theta_{\gamma'} = \Theta_{61}, \Theta_\delta = \Theta_{65}, \Theta_{\delta'} = \Theta_{68},$$

which is equivalent to

$$0, 714 > q \frac{1 + p\Theta_{61}}{1 + p'\Theta_{65}} \frac{1 + p\Theta_{64}}{1 + p'\Theta_{68}}. \quad (51)$$

Let's find the condition for subrectangle  $\{2, 11\}$  to intersect with  $\{213, 32\}$ :

$$\gamma - \gamma' > \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{63}, \Theta_{\gamma'} = \Theta_3, \Theta_\delta = \Theta_{20}, \Theta_{\delta'} = \Theta_{66},$$

which is equivalent to

$$0, 662 > q \frac{1 + p\Theta_3}{1 + p'\Theta_{20}} \frac{1 + p\Theta_{63}}{1 + p'\Theta_{66}}. \quad (52)$$

The condition (51) follows from (52), because

$$\begin{aligned} 0, 662 > q \frac{1 + p'\Theta_{30}}{1 + p\Theta_3} \frac{1 + p'\Theta_{66}}{1 + p\Theta_{63}} &< 0, 714 \frac{1 + p'\Theta_{65}}{1 + p\Theta_{61}} \frac{1 + p'\Theta_{68}}{1 + p\Theta_{64}} \\ &\quad \updownarrow \\ \frac{1 + p'\Theta_{20}}{1 + p'\Theta_{65}} \frac{1 + p'\Theta_{66}}{1 + p'\Theta_{68}} \frac{1 + p\Theta_{61}}{1 + p\Theta_3} \frac{1 + p\Theta_{64}}{1 + p\Theta_{63}} &< 1, 078, \end{aligned}$$

which is easily checked.

In consideration of (52), we come to  $\{2, 11\}$ .

Now suppose that (53), the negation of (52), takes place:

$$0,662 \leq q \frac{1+p\Theta_3}{1+p'\Theta_{20}} \frac{1+p\Theta_{63}}{1+p'\Theta_{66}}. \quad (53)$$

Return to condition (33). Let's see when the subrectangle  $\{11,1\}$  is left-normal. The condition

$$1,4(\gamma - \gamma') < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{68}, \Theta_{\gamma'} = \Theta_{65}, \Theta_\delta = \Theta_{92}, \Theta_{\delta'} = \Theta_{95},$$

expands to

$$0,443 < q \frac{1+p\Theta_{65}}{1+p'\Theta_{92}} \frac{1+p\Theta_{68}}{1+p'\Theta_{95}}$$

and follows from (53). Thus in case  $a_{i_2} \neq 3$  we can use the following  $\Theta$ 's in (33):

$$\Theta_\gamma = \Theta_{66}, \Theta_{\gamma'} = \Theta_{63}, \Theta_\delta = \Theta_{70}, \Theta_{\delta'} = \Theta_{94},$$

so (33) expands to

$$0,556 < q \frac{1+p\Theta_{63}}{1+p'\Theta_{70}} \frac{1+p\Theta_{66}}{1+p'\Theta_{94}}. \quad (54)$$

Overall, if  $a_{i_2} \neq 3$ , then we can assume that

$$0,556 \geq q \frac{1+p\Theta_{63}}{1+p'\Theta_{70}} \frac{1+p\Theta_{66}}{1+p'\Theta_{94}}. \quad (55)$$

Consider subrectangle  $\{33,213\}$ . We will show that it intersects with  $\{2,2\}$ . The condition

$$\gamma - \gamma' < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{30}, \Theta_{\gamma'} = \Theta_{25}, \Theta_\delta = \Theta_{30}, \Theta_{\delta'} = \Theta_{63},$$

expands to

$$0,638 < q \frac{1+p\Theta_{25}}{1+p'\Theta_{30}} \frac{1+p\Theta_{30}}{1+p'\Theta_{63}}. \quad (56)$$

Condition (56) follows from (53), if

$$\begin{aligned} 0,662 \frac{1+p'\Theta_{20}}{1+p\Theta_3} \frac{1+p'\Theta_{66}}{1+p\Theta_{63}} &> 0,638 \frac{1+p'\Theta_{30}}{1+p\Theta_{25}} \frac{1+p'\Theta_{63}}{1+p\Theta_{30}} \\ &\Updownarrow \\ 1,037 &> \frac{1+p'\Theta_{30}}{1+p'\Theta_{20}} \frac{1+p'\Theta_{63}}{1+p'\Theta_{66}} \frac{1+p\Theta_3}{1+p\Theta_{25}} \frac{1+p\Theta_{63}}{1+p\Theta_{30}}. \end{aligned}$$

Transform this inequality, increasing the right part:

$$\begin{aligned} 1,037 &> \frac{1+0,8p'+0,15p'^2}{1+0,85p'+0,15p'^2} \frac{1+0,71p+0,13p^2}{1+0,66p+0,13p^2} = \\ &= \left(1 - \frac{0,05p'}{1+0,85p'+0,15p'^2}\right) \left(1 + \frac{0,05p}{1+0,66p+0,13p^2}\right). \end{aligned}$$

Checking the last inequality by substituting  $p'$  with 0,25 and  $p$  with 0,8.



Showing that  $\{33, 213\}$  is left-normal. The following condition should take place:

$$\gamma - \gamma' > 1, 4(\delta - \delta'),$$

where

$$\Theta_\gamma = [0; 333\overline{31}] = 0, 302806, \Theta_{\gamma'} = \Theta_{22}, \Theta_\delta = \Theta_{31}, \Theta_{\delta'} = \Theta_{33},$$

which expands to

$$0, 85 > q \frac{1 + p\Theta_{22}}{1 + p'\Theta_{31}} \frac{1 + p\Theta_\gamma}{1 + p'\Theta_{33}}. \quad (57)$$

Now show that (57) follows from (55) in case  $a_{i_2} \neq 3$ . We need to check the inequality

$$\begin{aligned} 0, 556 \frac{1 + p'\Theta_{70}}{1 + p\Theta_{63}} \frac{1 + p'\Theta_{94}}{1 + p\Theta_{66}} &< 0, 85 \frac{1 + p'\Theta_{31}}{1 + p\Theta_{22}} \frac{1 + p'\Theta_{33}}{1 + p\Theta_\gamma} \\ &\Updownarrow \\ \frac{1 + p'\Theta_{70}}{1 + p'\Theta_{31}} \frac{1 + p'\Theta_{94}}{1 + p'\Theta_{33}} \frac{1 + p\Theta_{22}}{1 + p\Theta_{63}} \frac{1 + p\Theta_\gamma}{1 + p\Theta_{66}} &< 1, 5. \end{aligned}$$

If  $a_{i_2} = 3$ , then (57) follows from (35). Indeed, check the following inequality:

$$\begin{aligned} 0, 74 \frac{1 + p'\Theta_{70}}{1 + p\Theta_{63}} \frac{1 + p'\Theta_{90}}{1 + p\Theta_{66}} &< 0, 85 \frac{1 + p'\Theta_{31}}{1 + p\Theta_{21}} \frac{1 + p'\Theta_{33}}{1 + p\Theta_\gamma} \\ &\Updownarrow \\ \frac{1 + p'\Theta_{70}}{1 + p'\Theta_{31}} \frac{1 + p'\Theta_{90}}{1 + p\Theta_{33}} \frac{1 + p\Theta_{22}}{1 + p\Theta_{63}} \frac{1 + p\Theta_\gamma}{1 + p\Theta_{66}} &< 1, 15. \end{aligned}$$

Increasing the lhs, replacing  $p'$  with  $0, 33$  (since  $a_{i_2} = 3$ ) and  $p$  with  $0, 25$  and checking the inequality.

The next step is to show that the subrectangles  $\{33, 213\}$  and  $\{33, 212\}$  intersect. We will check the inequality

$$\gamma - \gamma' > \delta - \delta'$$

for

$$\Theta_\gamma = \Theta_{25}, \Theta_{\gamma'} = \Theta_{23}, \Theta_\delta = \Theta_{32}, \Theta_{\delta'} = \Theta_{35},$$

which is equivalent to

$$0, 9 > q \frac{1 + p\Theta_{23}}{1 + p'\Theta_{32}} \frac{1 + p\Theta_{25}}{1 + p'\Theta_{35}}. \quad (58)$$

As with the inequality (57), the inequality (58) follows from (55) in case  $a_{i_2} \neq 3$ . If  $a_{i_2} = 3$ , then (58) follows from (35).

It is easy to check that  $\{23, 213\}$  intersects with  $\{33, 212\}$ .

Now let's check that the subrectangle  $\{23, 213\}$  is good. The following inequality should take place:

$$\gamma - \gamma' < 3, 8(\delta - \delta'),$$

where

$$\Theta_\gamma = \Theta_{21}, \Theta_{\gamma'} = \Theta_{15}, \Theta_\delta = \Theta_{29}, \Theta_{\delta'} = \Theta_{33},$$

which expands to

$$0, 569 < q \frac{1 + p\Theta_{15}}{1 + p'\Theta_{29}} \frac{1 + p\Theta_{21}}{1 + p'\Theta_{33}}. \quad (59)$$

The condition (59) follows from (53), if

$$0,662 \frac{1+p'\Theta_{20}}{1+p\Theta_3} \frac{1+p'\Theta_{66}}{1+p\Theta_{63}} > 0,569 \frac{1+p'\Theta_{29}}{1+p\Theta_{15}} \frac{1+p'\Theta_{33}}{1+p\Theta_{21}}$$

$$\Updownarrow$$

$$\frac{1+p\Theta_{15}}{1+p\Theta_3} \frac{1+p\Theta_{21}}{1+p\Theta_{63}} \frac{1+p'\Theta_{20}}{1+p'\Theta_{29}} \frac{1+p'\Theta_{66}}{1+p'\Theta_{33}} > 0,85.$$

By replacing  $p'$  with 0,25 and  $p$  with 0,8, we will decrease the lhs. The resulting inequality is true, so (59) is checked.

Easily check the intersection of  $\{23, 213\}$  with the next subrectangle  $\{23, 212\}$ .

Checking that  $\{23, 212\}$  intersects with  $\{23, 211\}$ . The condition

$$\gamma - \gamma' > \delta - \delta'$$

for

$$\Theta_\gamma = \Theta_{19}, \Theta_{\gamma'} = \Theta_{16}, \Theta_\delta = \Theta_{38}, \Theta_{\delta'} = \Theta_{41}$$

expands to

$$0,875 > q \frac{1+p\Theta_{16}}{1+p'\Theta_{38}} \frac{1+p\Theta_{19}}{1+p'\Theta_{41}}$$

and follows from (57).

The choice of  $\Theta_{\gamma'}$  and  $\Theta_\delta$  is justified, if the subrectangle  $\{23, 212\}$  is left-normal. For this we need the following condition to take place:

$$\gamma - \gamma' > 1,4(\delta - \delta'),$$

where

$$\Theta_\gamma = \Theta_{17}, \Theta_{\gamma'} = \Theta_{15}, \Theta_\delta = [0; 2123\overline{31}] = 0,370705, \Theta_{\delta'} = \Theta_{39},$$

so obtain

$$0,91 > q \frac{1+p\Theta_{15}}{1+p'\Theta_\delta} \frac{1+p\Theta_{17}}{1+p'\Theta_{39}},$$

which follows from (57).

Now show that the subrectangle  $\{23, 211\}$  intersects with  $\{2, 1\}$ . The following condition should take place:

$$\gamma - \gamma' > \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{63}, \Theta_{\gamma'} = \Theta_{18}, \Theta_\delta = \Theta_{54}, \Theta_{\delta'} = \Theta_{70},$$

, which expands to

$$0,80 > q \frac{1+p\Theta_{18}}{1+p'\Theta_{54}} \frac{1+p\Theta_{63}}{1+p'\Theta_{70}}. \tag{60}$$

If  $a_{i_2} \neq 3$ , then (60) follows from (55): the inequality

$$0,556 \frac{1+p'\Theta_{70}}{1+p\Theta_{63}} \frac{1+p'\Theta_{94}}{1+p\Theta_{66}} < 0,8 \frac{1+p'\Theta_{54}}{1+p\Theta_{18}} \frac{1+p'\Theta_{70}}{1+p\Theta_{63}}$$

$$\Updownarrow$$

$$\frac{1+p'\Theta_{94}}{1+p'\Theta_{54}} \frac{1+p\Theta_{18}}{1+p\Theta_{66}} < 1,43$$

is checked by setting  $p'$  to 0,8 and  $p$  to 0,25.

If  $a_{i_2} = 3$ , then (60) follows from (35). Checking that

$$0,74 \frac{1+p'\Theta_{70}}{1+p\Theta_{63}} \frac{1+p'\Theta_{90}}{1+p\Theta_{66}} < 0,8 \frac{1+p'\Theta_{54}}{1+p\Theta_{18}} \frac{1+p'\Theta_{70}}{1+p\Theta_{63}}$$

$$\updownarrow$$

$$\frac{1+p'\Theta_{94}}{1+p'\Theta_{54}} \frac{1+p\Theta_{18}}{1+p\Theta_{66}} < 1,08$$

by substituting  $p'$  with  $\frac{1}{3}$  and  $p$  with 0,25.

In case  $\Delta'$  is defined with (20c) or (20d), then we are done. In cases (20a) and (20b) we also need to consider the subrectangle  $\{3, 1\}$ .

At first show that it is good. To start with, show that  $\{3, 12\}$  is right-normal. Check that

$$\gamma - \gamma' > 1,4(\delta - \delta')$$

for

$$\Theta_\gamma = \Theta_{28}, \Theta_{\gamma'} = \Theta_{22}, \Theta_{\delta'} = [0; 123\overline{31}] = 0,697556, \Theta_\delta = [0; 123\overline{1}] = 0,693606,$$

which expands to

$$0,715 > q \frac{1+p\Theta_{22}}{1+p'\Theta_\delta} \frac{1+p\Theta_{28}}{1+p'\Theta_{\delta'}}. \quad (61)$$

Inequality (61) follows from (35), because

$$0,74 \frac{1+p'\Theta_{70}}{1+p\Theta_{63}} \frac{1+p'\Theta_{90}}{1+p\Theta_{66}} < 0,715 \frac{1+p'\Theta_\delta}{1+p\Theta_{22}} \frac{1+p'\Theta_{\delta'}}{1+p\Theta_{28}}$$

$$\updownarrow$$

$$\frac{1+p\Theta_{22}}{1+p\Theta_{63}} \frac{1+p\Theta_{28}}{1+p\Theta_{66}} \frac{1+p'\Theta_{70}}{1+p'\Theta_\delta} \frac{1+p'\Theta_{90}}{1+p'\Theta_{\delta'}} < 0,965.$$

Checking the last inequality by setting both  $p$  and  $p'$  to 0,25 and increasing the lhs.

Now check the condition

$$\delta - \delta' > \delta - \delta'$$

for

$$\Theta_\gamma = \Theta_{25}, \Theta_{\gamma'} = \Theta_3, \Theta_\delta = \Theta_{81}, \Theta_{\delta'} = \Theta_{83},$$

expanding to

$$0,693 > q \frac{1+p\Theta_3}{1+p'\Theta_{81}} \frac{1+p\Theta_{25}}{1+p'\Theta_{83}}. \quad (62)$$

The inequality (62) follows from (35), because

$$0,74 \frac{1+p'\Theta_{70}}{1+p\Theta_{63}} \frac{1+p'\Theta_{90}}{1+p\Theta_{66}} < 0,693 \frac{1+p'\Theta_{81}}{1+p\Theta_3} \frac{1+p'\Theta_{83}}{1+p\Theta_{25}}$$

$$\updownarrow$$

$$\frac{1+p\Theta_3}{1+p\Theta_{63}} \frac{1+p\Theta_{25}}{1+p\Theta_{66}} \frac{1+p'\Theta_{70}}{1+p'\Theta_{81}} \frac{1+p'\Theta_{90}}{1+p'\Theta_{83}} < 0,935.$$

Again, the last inequality is checked by setting  $p$  and  $p'$  to 0,25.

Now show that  $\{3, 1\}$  and  $\{2, 1\}$  intersect. The condition

$$\gamma - \gamma' < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{30}, \Theta_{\gamma'} = \Theta_{25}, \Theta_\delta = \Theta_{71}, \Theta_{\delta'} = \Theta_{89},$$

expands to

$$0,338 < q \frac{1+p\Theta_{25}}{1+p'\Theta_{71}} \frac{1+p\Theta_{30}}{1+p'\Theta_{89}}. \quad (63)$$

The inequality (63) follows from (46), because

$$\begin{aligned} 0,558 \frac{1+p'\Theta_{63}}{1+p\Theta_{35}} \frac{1+p'\Theta_{70}}{1+p\Theta_{63}} &> 0,338 \frac{1+p'\Theta_{71}}{1+p\Theta_{25}} \frac{1+p'\Theta_{89}}{1+p\Theta_{30}} \\ &\Downarrow \\ 1,65 &> \frac{1+p\Theta_{35}}{1+p\Theta_{25}} \frac{1+p\Theta_{63}}{1+p\Theta_{30}} \frac{1+p'\Theta_{71}}{1+p'\Theta_{63}} \frac{1+p'\Theta_{89}}{1+p'\Theta_{70}}, \end{aligned}$$

which is easily checked by substituting both  $p$  and  $p'$  with 0,8.

## 7 Induction, $i_1 \equiv i_2 \pmod{2}$

This section deals with the case  $i_1 \equiv i_2 \pmod{2}$ . Again, let  $\Delta = \{a_{i_1}, \dots, a_{i_2}\}$  be a horizontal rectangle, satisfying conditions from sections 3 and 4.

As in section (6), we will assume that both  $i_1$  and  $i_2$  are even; for the different parity the same logic can be repeated, with bounds in the inequalities swapped and illustrations reflected.

### 7.1 Case $\{3, 2\}$ is right-normal

We start with the case

$$\gamma - \gamma' > \delta - \delta', \quad (64)$$

where

$$\Theta_\gamma = \Theta_{25}, \Theta_{\gamma'} = \Theta_3, \Theta_\delta = \Theta_{66}, \Theta_{\delta'} = \Theta_{63},$$

*Freiman ceases to give explanatory illustrations to inequalities like (64) in this section and suggests the reader to make them on their own.*

Inequality (64) expands to

$$0, 31 > q \frac{1 + p\Theta_3}{1 + p'\Theta_{63}} \frac{1 + p\Theta_{25}}{1 + p'\Theta_{66}}. \quad (65)$$

The rounding is done to a higher precision so that (64) and (67) both follow from (65).

The constants  $\Theta_{25}$  and  $\Theta_3$  are chosen such that the subrectangle  $\{3, 2\}$  which will occur in the further splitting is right-normal. This condition allows us to choose the largest possible constant in the lhs of (65).

So, the following condition should take place:

$$\gamma - \gamma' > 1, 4(\delta - \delta'), \quad (66)$$

where

$$\Theta_\gamma = \Theta_{28}, \Theta_{\gamma'} = \Theta_{22}, \Theta_\delta = \Theta_{64}, \Theta_{\delta'} = \Theta_{61},$$

which expands to

$$0, 345 > q \frac{1 + p\Theta_{22}}{1 + p'\Theta_{61}} \frac{1 + p\Theta_{28}}{1 + p'\Theta_{64}}. \quad (67)$$

Let's show that (67) follows from (65):

$$0, 344 \frac{1 + p'\Theta_{61}}{1 + p\Theta_{22}} > 0, 31 \frac{1 + p'\Theta_{66}}{1 + p\Theta_3} \quad (68)$$

$$\Updownarrow \quad (69)$$

$$1, 1 > \frac{1 + p\Theta_{22}}{1 + p\Theta_3} \frac{1 + p'\Theta_{66}}{1 + p'\Theta_{61}}. \quad (71)$$

Checking it by replacing  $p$  and  $p'$  with their upper bound 0.8 and increasing the rhs.

In consideration of (65), in case  $\Delta'$  is defined with (15) and (16), we can take  $\{1, \}$ ,  $\{2, \}$ , and  $\{3, \}$ , and in case (17) and (18) subrectangles  $\{1, \}$  and  $\{2, \}$  are enough.

In the rest section we will assume that (65) doesn't take place, that is,

$$0, 31 \leq q \frac{1 + p\Theta_3}{1 + p'\Theta_{63}} \frac{1 + p\Theta_{25}}{1 + p'\Theta_{66}}. \quad (72)$$

## 7.2 Name

Consider condition

$$\gamma - \gamma' > \delta - \delta', \quad (73)$$

where

$$\Theta_\gamma = \Theta_{63}, \Theta_{\gamma'} = \Theta_{36}, \Theta_\delta = \Theta_{66}, \Theta_{\delta'} = \Theta_{63},$$

which expands to

$$0,634 > q \frac{1+p\Theta_{36}}{1+p'\Theta_{63}} \frac{1+p\Theta_{63}}{1+p'\Theta_{66}}. \quad (74)$$

To justify the choice  $\Theta_\gamma = \Theta_{\gamma'} = \Theta_{63}$ , we need to check

$$\gamma - \gamma' > 1,4(\delta - \delta'), \quad (75)$$

where

$$\Theta_\gamma = \Theta_{64}, \Theta_{\gamma'} = \Theta_{61}, \Theta_\delta = \Theta_{64}, \Theta_{\delta'} = \Theta_{61},$$

which expands to

$$0,714 > q \frac{1+p\Theta_{61}}{1+p'\Theta_{61}} \frac{1+p\Theta_{64}}{1+p'\Theta_{64}}. \quad (76)$$

The last inequality follows from (74), if

$$\frac{1+p'\Theta_{63}}{1+p'\Theta_{61}} \frac{1+p'\Theta_{66}}{1+p'\Theta_{64}} \frac{1+p\Theta_{61}}{1+p\Theta_{36}} \frac{1+p\Theta_{64}}{1+p\Theta_{63}} < 1,125, \quad (77)$$

which is easily checked by substituting  $p = p' = 0.8$ , as in (68).

If (73) takes place, then take subrectangles  $\{1, \}$  and  $\{2, \}$ . Thus, in consideration of (74), cases (17) and (18) are over.

Now turn to cases (15) and (16) (IIa). We will show that

$$\gamma - \gamma' < \delta - \delta', \quad (78)$$

where

$$\Theta_\gamma = \Theta_{30}, \Theta_{\gamma'} = \Theta_{25}, \Theta_\delta = \Theta_{59}, \Theta_{\delta'} = \Theta_3,$$

which can be rewritten as

$$0,3375 < q \frac{1+p\Theta_{25}}{1+p'\Theta_3} \frac{1+p\Theta_{30}}{1+p'\Theta_{59}}. \quad (79)$$

The last inequality follows from (72), if

$$1,09 < \frac{1+p'\Theta_{63}}{1+p'\Theta_3} \frac{1+p'\Theta_{66}}{1+p'\Theta_{59}} \frac{1+p\Theta_{30}}{1+p\Theta_3},$$

which is checked by substituting  $p = p' = 0,25$ .

The inequality (78) shows that, in consideration of (74) and in case (15), the subrect-angle  $\{3, 2\}$  intersects with  $\{2, \}$ , even if  $\{3, 2\}$  is right-shortened.

If  $\Delta$  is left-shortened, then the splitting is over. If it is left-normal, then subrectangles  $J_k = \{3, 3\}$  are added.

Check that, for example,  $J_1 = \{3, 3\}$  is good.

We need

$$\gamma - \gamma' < 3,8(\delta - \delta'), \quad (80)$$

where

$$\Theta_\gamma = \Theta_{28}, \Theta_{\gamma'} = \Theta_1, \Theta_\delta = \Theta_{28}, \Theta_{\delta'} = \Theta_1,$$

which expands to

$$0,264 < q \frac{1+p\Theta_1}{1+p'\Theta_1} \frac{1+p\Theta_{28}}{1+p'\Theta_{28}} \quad (81)$$

and follows from (72), if

$$1,17 > \frac{1+p\Theta_3}{1+p\Theta_1} \frac{1+p\Theta_{25}}{1+p\Theta_{28}} \frac{1+p'\Theta_1}{1+p'\Theta_{63}} \frac{1+p'\Theta_{28}}{1+p'\Theta_{66}},$$

which is obvious.

*Here Freiman links the  $\sqrt{21}$  proof from §9. I will translate it soon.*

It remains to deal with (16) (IIb).

Suppose that the following inequality takes place:

$$\gamma - \gamma' < \delta - \delta' \quad (82)$$

with

$$\Theta_\gamma = \Theta_{30}, \Theta_{\gamma'} = \Theta_{25}, \Theta_\delta = \Theta_{63}, \Theta_{\delta'} = \Theta_{36}.$$

Inequality (82) is rewritten as follows. Instead of 0,703 in the lhs take constant 0,73 to assure  $\{3, 2\}$  normality:

$$0,73 < q \frac{1+p\Theta_{25}}{1+p'\Theta_{36}} \frac{1+p\Theta_{30}}{1+p'\Theta_{63}}. \quad (83)$$

Subrectangle  $\{3, 2\}$  is normal, if

$$1,4(\gamma - \gamma') < \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{28}, \Theta_{\gamma'} = \Theta_{22}, \Theta_\delta = \Theta_{64}, \Theta_{\delta'} = \Theta_{61},$$

which expands to

$$0,6773 < q \frac{1+p\Theta_{22}}{1+p'\Theta_{61}} \frac{1+p\Theta_{28}}{1+p'\Theta_{64}}$$

and follows from (83), if

$$1,076 > \frac{1+p'\Theta_{61}}{1+p'\Theta_{36}} \frac{1+p'\Theta_{64}}{1+p'\Theta_{63}} \frac{1+p\Theta_{30}}{1+p\Theta_{22}},$$

which is checked as (68).

In addition to subrectangles  $\{1, \}$  and  $\{2, \}$  we can now take  $\{3, 2\}$ , and case (16) is done, if (83), (74), and (72) all take place.

Note that (83) does not depend on (74). We will need it below. If (83) doesn't take place, that is,

$$0,73 \geq q \frac{1+p\Theta_{25}}{1+p'\Theta_{36}} \frac{1+p\Theta_{30}}{1+p'\Theta_{63}}, \quad (84)$$

then in case (16) the subrectangles  $\{2, \}$  and  $\{3, 2\}$  may not intersect when

$$\Delta'_1(2) + \Delta'_2(2) > \Delta''_1(3) + \Delta''_2(2).$$

The system of subrectangles covering the interval  $(\Delta_1''(3) + \Delta_2''(2); \Delta_1'(2) + \Delta_2'(2))$  will be found further.

Suppose that (74) doesn't take place, that is,

$$0,634 \leq q \frac{1+p\Theta_{36}}{1+p'\Theta_{63}} \frac{1+p\Theta_{63}}{1+p'\Theta_{66}}. \quad (85)$$

At first, consider subrectangles  $\{1, \}$  and  $\{2, 1\}$ . Rectangle  $\Delta$  is good, so they intersect. Showing that  $\{2, 1\}$  is good. We need the following:

$$3,8(\gamma - \gamma') > \delta - \delta', \quad (86)$$

where

$$\Theta_\gamma = \Theta_{64}, \quad \Theta_{\gamma'} = \Theta_{29}, \quad \Theta_\delta = \Theta_{95}, \quad \Theta_{\delta'} = \Theta_{65},$$

which expands to

$$1,36 > q \frac{1+p\Theta_{29}}{1+p'\Theta_{65}} \frac{1+p\Theta_{64}}{1+p'\Theta_{95}}$$

and is easily checked.

Now consider subrectangle  $\{3, 1\}$ , if it is good. The following is required:

$$3,8(\gamma - \gamma') > \delta - \delta',$$

where

$$\Theta_\gamma = \Theta_{28}, \quad \Theta_{\gamma'} = \Theta_1, \quad \Theta_\delta = \Theta_{95}, \quad \Theta_{\delta'} = \Theta_{65},$$

which expands to

$$0,696 > q \frac{1+p\Theta_1}{1+p'\Theta_{65}} \frac{1+p\Theta_{28}}{1+p'\Theta_{95}}. \quad (87)$$

Let the negation of (87), the inequality (88), take place:

$$0,696 \leq q \frac{1+p\Theta_1}{1+p'\Theta_{65}} \frac{1+p\Theta_{28}}{1+p'\Theta_{95}}. \quad (88)$$

Then considering the subrectangle  $\{3, 11\}$  and showing that it intersects with  $\{2, 1\}$ . The following inequality is needed:

$$\gamma - \gamma' < \delta - \delta', \quad (89)$$



$\Theta_1 = [0; 3\bar{1}] = 0,263762$	$\Theta_{35} = [0; 2\bar{1}2\bar{1}3\bar{1}\bar{2}] = 0,36549$	$\Theta_{67} = [0; 1\bar{1}3\bar{1}\bar{2}] = 0,56635$
$\Theta_2 = [0; 3\bar{1}2\bar{1}\bar{3}] = 0,267649$	$\Theta_{36} = [0; 2\bar{1}] = 0,36602$	$\Theta_{68} = [0; 1\bar{1}3\bar{1}\bar{1}] = 0,566423$
$\Theta_3 = [0; 3\bar{1}\bar{2}] = 0,26794$	$\Theta_{37} = [0; 2\bar{1}2\bar{1}\bar{1}\bar{3}] = 0,36779$	$\Theta_{69} = [0; 1\bar{1}2\bar{1}\bar{3}] = 0,57600$
$\Theta_4 = [0; 3\bar{1}23\bar{1}\bar{1}] = 0,270448$	$\Theta_{38} = [0; 2\bar{1}23\bar{1}\bar{2}] = 0,37119$	$\Theta_{70} = [0; 1\bar{1}2\bar{1}3\bar{1}\bar{2}] = 0,57602$
$\Theta_5 = [0; 3\bar{1}23\bar{1}\bar{2}] = 0,270710$	$\Theta_{39} = [0; 2\bar{1}2\bar{3}\bar{1}] = 0,371249$	$\Theta_{71} = [0; 1\bar{1}\bar{2}] = 0,57735$
$\Theta_6 = [0; 3\bar{1}23\bar{1}] = 0,270738$	$\Theta_{40} = [0; 2\bar{1}\bar{1}\bar{3}] = 0,378537$	$\Theta_{72} = [0; 1\bar{1}23\bar{1}\bar{2}] = 0,59032$
$\Theta_7 = [0; 3\bar{1}\bar{1}\bar{1}\bar{3}] = 0,27459$	$\Theta_{41} = [0; 2\bar{1}\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,37858$	$\Theta_{73} = [0; 1\bar{1}\bar{1}\bar{1}\bar{3}] = 0,609108$
$\Theta_8 = [0; 3\bar{1}\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,27462$	$\Theta_{42} = [0; 2\bar{1}\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,379018$	$\Theta_{74} = [0; 1\bar{1}\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,60923$
$\Theta_9 = [0; 3\bar{1}\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,274847$	$\Theta_{43} = [0; 2\bar{1}\bar{1}\bar{1}\bar{2}] = 0,37963$	$\Theta_{75} = [0; 1\bar{1}\bar{1}\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,620981$
$\Theta_{10} = [0; 3\bar{1}\bar{1}\bar{1}\bar{2}] = 0,27517$	$\Theta_{44} = [0; 2\bar{1}\bar{1}\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,383091$	$\Theta_{76} = [0; 1\bar{1}\bar{1}\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,62141$
$\Theta_{11} = [0; 3\bar{1}\bar{1}\bar{2}] = 0,27954$	$\Theta_{45} = [0; 2\bar{1}\bar{1}\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,38326$	$\Theta_{77} = [0; 1\bar{1}\bar{1}\bar{1}\bar{1}\bar{3}] = 0,621460$
$\Theta_{12} = [0; 3\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,280392$	$\Theta_{46} = [0; 2\bar{1}\bar{1}\bar{1}\bar{1}\bar{3}] = 0,383272$	$\Theta_{78} = [0; 1\bar{1}\bar{1}23\bar{1}\bar{2}] = 0,62881$
$\Theta_{13} = [0; 3\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,28097$	$\Theta_{47} = [0; 2\bar{1}\bar{1}23\bar{1}\bar{2}] = 0,38605$	$\Theta_{79} = [0; 1\bar{1}\bar{1}\bar{2}] = 0,63400$
$\Theta_{14} = [0; 3\bar{1}\bar{1}\bar{3}] = 0,28105$	$\Theta_{48} = [0; 2\bar{1}\bar{1}23\bar{1}] = 0,386033$	$\Theta_{80} = [0; 1\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,63839$
$\Theta_{15} = [0; 323\bar{1}] = 0,290550$	$\Theta_{49} = [0; 2\bar{1}\bar{1}23\bar{3}\bar{1}] = 0,386237$	$\Theta_{81} = [0; 1\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,63910$
$\Theta_{16} = [0; 323\bar{1}\bar{2}] = 0,29062$	$\Theta_{50} = [0; 2\bar{1}\bar{1}22\bar{1}] = 0,38651$	$\Theta_{82} = [0; 1\bar{1}\bar{1}\bar{3}] = 0,641742$
$\Theta_{17} = [0; 323\bar{3}\bar{1}] = 0,291242$	$\Theta_{51} = [0; 2\bar{1}\bar{1}\bar{2}] = 0,38800$	$\Theta_{83} = [0; 123\bar{1}\bar{2}] = 0,69399$
$\Theta_{18} = [0; 322\bar{1}] = 0,29216$	$\Theta_{52} = [0; 2\bar{1}\bar{1}3\bar{3}\bar{1}] = 0,389648$	$\Theta_{84} = [0; 122\bar{1}3\bar{1}\bar{2}] = 0,70225$
$\Theta_{19} = [0; 32\bar{1}] = 0,29709$	$\Theta_{53} = [0; 2\bar{1}\bar{1}32\bar{1}] = 0,389916$	$\Theta_{85} = [0; 1223\bar{1}\bar{2}] = 0,70938$
$\Theta_{20} = [0; 32\bar{1}3\bar{1}\bar{2}] = 0,29774$	$\Theta_{54} = [0; 2\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,39076$	$\Theta_{86} = [0; 1222\bar{1}] = 0,70783$
$\Theta_{21} = [0; 32\bar{1}\bar{3}] = 0,297773$	$\Theta_{55} = [0; 2\bar{1}\bar{1}\bar{3}] = 0,390891$	$\Theta_{87} = [0; 12\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,71903$
$\Theta_{22} = [0; 333\bar{1}] = 0,302444$	$\Theta_{56} = [0; 223\bar{1}] = 0,409544$	$\Theta_{88} = [0; 12\bar{1}\bar{1}\bar{1}3\bar{1}\bar{2}] = 0,725381$
$\Theta_{23} = [0; 333\bar{1}\bar{2}] = 0,30025$	$\Theta_{57} = [0; 223\bar{1}\bar{2}] = 0,40968$	$\Theta_{89} = [0; \bar{1}\bar{2}] = 0,73206$
$\Theta_{24} = [0; 332\bar{1}] = 0,30330$	$\Theta_{58} = [0; 2\bar{2}\bar{1}] = 0,42265$	$\Theta_{90} = [0; 12\bar{1}3\bar{1}\bar{2}] = 0,73620$
$\Theta_{25} = [0; 33\bar{1}\bar{2}] = 0,30600$	$\Theta_{59} = [0; 22\bar{1}3\bar{1}\bar{2}] = 0,42398$	$\Theta_{91} = [0; 12\bar{1}\bar{3}] = 0,73624$
$\Theta_{26} = [0; 33\bar{1}2\bar{1}\bar{3}] = 0,30603$	$\Theta_{60} = [0; 22\bar{1}\bar{3}] = 0,424042$	$\Theta_{92} = [0; 133\bar{1}] = 0,765465$
$\Theta_{27} = [0; 33\bar{1}3\bar{1}\bar{2}] = 0,30638$	$\Theta_{61} = [0; 233\bar{1}] = 0,433577$	$\Theta_{93} = [0; 133\bar{1}\bar{2}] = 0,76569$
$\Theta_{28} = [0; 33\bar{1}\bar{3}] = 0,306394$	$\Theta_{62} = [0; 233\bar{1}\bar{2}] = 0,43365$	$\Theta_{94} = [0; 13\bar{1}\bar{2}] = 0,78868$
$\Theta_{29} = [0; 2\bar{1}\bar{3}] = 0,358258$	$\Theta_{63} = [0; 23\bar{1}\bar{2}] = 0,44093$	$\Theta_{95} = [0; \bar{1}\bar{3}] = 0,791287$
$\Theta_{30} = [0; 2\bar{1}3\bar{1}\bar{2}] = 0,35859$	$\Theta_{64} = [0; 23\bar{1}] = 0,441742$	
$\Theta_{31} = [0; 2\bar{1}33\bar{1}\bar{1}] = 0,361292$	$\Theta_{65} = [0; 1\bar{1}\bar{3}] = 0,558256$	
$\Theta_{32} = [0; 2\bar{1}33\bar{1}\bar{2}] = 0,36158$	$\Theta_{66} = [0; 1\bar{1}3\bar{1}\bar{2}] = 0,55905$	
$\Theta_{33} = [0; 2\bar{1}33\bar{1}] = 0,361602$		
$\Theta_{34} = [0; 2\bar{1}2\bar{1}\bar{3}] = 0,365455$		

Figure 8: List of  $\Theta$ 's.

# Contents

<b>1</b>	<b>Introductory notation</b>	<b>1</b>
1.1	Markov and Lagrange values . . . . .	1
1.2	Centered sequence . . . . .	1
1.3	Rectangle . . . . .	1
1.4	Horizontal rectangle . . . . .	2
1.5	Subrectangle . . . . .	2
1.6	Geometrical interpretation . . . . .	2
<b>2</b>	<b>Calculations</b>	<b>3</b>
2.1	Length of $\Delta_1$ or $\Delta_2$ . . . . .	3
2.2	Rectangle aspect ratio . . . . .	3
<b>3</b>	<b>Rectangle boundaries</b>	<b>4</b>
3.1	Resection . . . . .	4
3.2	Shortened rectangle . . . . .	4
3.2.1	Case $i_1 \equiv i_2 \equiv 0 \pmod{2}$ . . . . .	4
3.2.2	Other cases . . . . .	5
3.3	Explanation of shortened . . . . .	5
3.4	How we ensure centeredness . . . . .	5
3.5	Formal . . . . .	6
3.5.1	Bounds for $\Delta'$ . . . . .	6
3.5.2	Bounds for $\Delta''$ . . . . .	8
3.5.3	Case $i_1 \not\equiv i_2 \pmod{2}$ . . . . .	8
<b>4</b>	<b>Good rectangle</b>	<b>9</b>
4.1	Definition . . . . .	9
4.2	Sufficient conditions of goodness . . . . .	9
4.2.1	Results . . . . .	9
4.2.2	Universal 2, 9 bound . . . . .	10
4.2.3	Case $i_1 \equiv i_2 \pmod{2}$ . . . . .	11
4.2.4	Case $i_1 \not\equiv i_2 \pmod{2}$ . . . . .	12
<b>5</b>	<b>Initial set of rectangles</b>	<b>14</b>
<b>6</b>	<b>Induction, <math>i_1 \not\equiv i_2 \pmod{2}</math></b>	<b>15</b>
6.1	Case $\{, 1\}$ is good . . . . .	15
6.2	Case $\Delta$ is left-shortened . . . . .	16
6.3	Case $\Delta$ is left-normal . . . . .	16
6.4	Case we can consider $\{2, 1\}$ . . . . .	18
6.5	Further plan . . . . .	19
6.6	List of subrectangles . . . . .	19
6.7	Correctness proof . . . . .	20
<b>7</b>	<b>Induction, <math>i_1 \equiv i_2 \pmod{2}</math></b>	<b>29</b>
7.1	Case $\{3, 2\}$ is right-normal . . . . .	29
7.2	Name . . . . .	30