Badly approximable points on planar curves and a problem of Davenport

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Abstract Let \( C \) be two times continuously differentiable curve in \( \mathbb{R}^2 \) with at least one point at which the curvature is non-zero. For any \( i, j \geq 0 \) with \( i + j = 1 \), let \( \text{Bad}(i, j) \) denote the set of points \( (x, y) \in \mathbb{R}^2 \) for which \( \max\{\|qx\|^{1/i}, \|qy\|^{1/j}\} > c/q \) for all \( q \in \mathbb{N} \). Here \( c = c(x, y) \) is a positive constant. Our main result implies that any finite intersection of such sets with \( C \) has full Hausdorff dimension. This provides a solution to a problem of Davenport dating back to the sixties.

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1 Introduction

A real number \( x \) is said to be badly approximable if there exists a positive constant \( c(x) \) such that
\[
\|qx\| > c(x) q^{-1} \quad \forall q \in \mathbb{N}.
\]
Here and throughout \( \| \cdot \| \) denotes the distance of a real number to the nearest integer. It is well known that set \( \text{Bad} \) of badly approximable numbers is of Lebesgue measure zero but of maximal Hausdorff dimension; i.e. \( \dim \text{Bad} = 1 \). In higher dimensions...
there are various natural generalizations of $\text{Bad}$. Restricting our attention to the plane $\mathbb{R}^2$, given a pair of real numbers $i$ and $j$ such that

$$0 \leq i, j \leq 1 \quad \text{and} \quad i + j = 1,$$

(1)
a point $(x, y) \in \mathbb{R}^2$ is said to be $(i, j)$-badly approximable if there exists a positive constant $c(x, y)$ such that

$$\max\{\|qx\|^{1/i}, \|qy\|^{1/j}\} > c(x, y) q^{-1} \quad \forall q \in \mathbb{N}.$$  

Denote by $\text{Bad}(i, j)$ the set of $(i, j)$-badly approximable points in $\mathbb{R}^2$. If $i = 0$, then we use the convention that $x^{1/i} := 0$ and so $\text{Bad}(0, 1)$ is identified with $\mathbb{R} \times \text{Bad}$. That is, $\text{Bad}(0, 1)$ consists of points $(x, y)$ with $x \in \mathbb{R}$ and $y \in \text{Bad}$. The roles of $x$ and $y$ are reversed if $j = 0$. In the case $i = j = 1/2$, the set under consideration is the standard set $\text{Bad}_2$ of simultaneously badly approximable points. It easily follows from classical results in the theory of metric Diophantine approximation that $\text{Bad}(i, j)$ is of (two-dimensional) Lebesgue measure zero and it was shown in [11] that $\dim \text{Bad}(i, j) = 2$.

1.1 The problem

Badly approximable numbers obeying various functional relations were first studied in the works of Cassels, Davenport and Schmidt from the fifties and sixties. In particular, Davenport [7] in 1964 proved that for any $n \geq 2$ there is a continuum set of $\alpha \in \mathbb{R}$ such that each of the numbers $\alpha, \alpha^2, \ldots, \alpha^n$ are all in $\text{Bad}$. In the same paper, Davenport [7, p. 52] states “Problems of a much more difficult character arise when the number of independent parameters is less than the dimension of simultaneous approximation. I do not know whether there is a set of $\alpha$ with the cardinal of the continuum such that the pair $(\alpha, \alpha^2)$ is badly approximable for simultaneous approximation.” Thus, given the parabola $\mathcal{V}_2 := \{(x, x^2) : x \in \mathbb{R}\}$, Davenport is asking the question:

$\text{Is the set } \mathcal{V}_2 \cap \text{Bad}_2 \text{ uncountable?}$

The goal of this paper is to answer this specific question for the parabola and consider the general setup involving an arbitrary planar curve $\mathcal{C}$ and $\text{Bad}(i, j)$. Without loss of generality, we assume that $\mathcal{C}$ is given as a graph

$$\mathcal{C}_f := \{(x, f(x)) : x \in I\}$$

for some function $f$ defined on an interval $I \subset \mathbb{R}$. It is easily seen that some restriction on the curve is required to ensure that $\mathcal{C} \cap \text{Bad}(i, j)$ is not empty. For example, let $L_{\alpha}$ denote the vertical line parallel to the $y$-axis passing through the point $(\alpha, 0)$ in the $(x, y)$-plane. Then, it is easily verified, see [4, §1.3] for the details, that

$$L_{\alpha} \cap \text{Bad}(i, j) = \emptyset$$
for any $\alpha \in \mathbb{R}$ satisfying $\lim \inf_{q \to \infty} q^{1/i} \| q\alpha \| = 0$. Note that the $\lim \inf$ under consideration is zero if $\alpha$ is a Liouville number. On the other hand, if the $\lim \inf$ is strictly positive, which it is if $\alpha \in \text{Bad}$, then

$$\dim (L_\alpha \cap \text{Bad}(i,j)) = 1.$$ 

This result is much harder to prove and is at the heart of the proof of Schmidt’s Conjecture recently established in [4]. The upshot of this discussion regarding vertical lines is that to build a general, coherent theory for badly approximable points on planar curves we need that the curve $C$ under consideration is in some sense ‘genuinely curved’. With this in mind, we will assume that $C$ is two times continuously differentiable and that there is at least one point on $C$ at which the curvature is non-zero. We shall refer to such a curve as a $C^{(2)}$ non-degenerate planar curve. In other words and more formally, a planar curve $C := C_f$ is $C^{(2)}$ non-degenerate if $f \in C^{(2)}(I)$ and there exits at least one point $x \in I$ such that

$$f''(x) \neq 0.$$ 

For these curves, it is reasonable to suspect that

$$\dim (C \cap \text{Bad}(i,j)) = 1.$$ 

If true, this would imply that $C \cap \text{Bad}(i,j)$ is uncountable and since the parabola $V_2$ is a $C^{(2)}$ non-degenerate planar curve we obtain a positive answer to Davenport’s question. To the best of our knowledge, there has been no progress with Davenport’s question to date. More generally, for planar curves (non-degenerate or not) the results stated above for vertical lines constitute the first and essentially only contribution. The main result proved in this paper shows that any finite intersection of $\text{Bad}(i,j)$ sets with a $C^{(2)}$ non-degenerate planar curve is of full dimension.

1.2 The results

**Theorem 1** Let $(i_1, j_1), \ldots, (i_d, j_d)$ be a finite number of pairs of real numbers satisfying (1). Let $C$ be a $C^{(2)}$ non-degenerate planar curve. Then

$$\dim \left( \bigcap_{t=1}^d \text{Bad}(i_t, j_t) \cap C \right) = 1.$$ 

A consequence of this theorem is the following statement regarding the approximation of real numbers by algebraic numbers. As usual, the height $H(\alpha)$ of an algebraic number is the maximum of the absolute values of the integer coefficients in its minimal defining polynomial.

**Corollary 1** The set of $x \in \mathbb{R}$ for which there exists a positive constant $c(x)$ such that

$$|x - \alpha| > c(x) H(\alpha)^{-3} \quad \forall \text{real algebraic numbers } \alpha \text{ of degree } \leq 2$$

is of full Hausdorff dimension.
The corollary represents the ‘quadratic’ analogue of Jarník’s classical $\dim \text{Bad} = 1$ statement and complements the well approximable results of Baker and Schmidt [5] and Davenport and Schmidt [8]. It also makes a contribution to Problems 24, 25 and 26 in [6, §10.2]. To deduce the corollary from the theorem, we exploit the equivalent dual form representation of the set $\text{Bad}(i, j)$. A point $(x, y) \in \text{Bad}(i, j)$ if there exists a positive constant $c(x, y)$ such that

$$\max\{|A|^{1/j}, |B|^{1/j}\} \|Ax - By\| > c(x, y) \quad \forall (A, B) \in \mathbb{Z}^2 \setminus \{(0, 0)\}. \quad (2)$$

Then with $d = 1$, $i = j = 1/2$ and $C = \mathcal{V}_2$, the theorem implies that

$$\dim \left\{x \in \mathbb{R} : \max\{|A|^2, |B|^2\} \|Ax - Bx^2\| > c(x) \quad \forall (A, B) \in \mathbb{Z}^2 \setminus \{(0, 0)\} \right\} = 1.$$

It can be verified that this is the statement of the corollary formulated in terms of integer polynomials.

Straight lines are an important class of $C^{(2)}$ planar curves not covered by Theorem 1. In view of the discussion in Sect. 1.1, this is to be expected since the conclusion of the theorem is false for lines in general. Indeed, it is only valid for a vertical line $L_\alpha$ if $\alpha$ satisfies the Diophantine condition $\lim_{q \to \infty} \inf q^{1/2} \|q\alpha\| > 0$. The following result provides an analogous statement for non-vertical lines.

**Theorem 2** Let $(i_1, j_1), \ldots, (i_d, j_d)$ be a finite number of pairs of real numbers satisfying (1). Given $\alpha, \beta \in \mathbb{R}$, let $L_{\alpha, \beta}$ denote the line defined by the equation $y = \alpha x + \beta$. Suppose there exists $\epsilon > 0$ such that

$$\lim_{q \to \infty} q^{1/2 - \epsilon} \|q\alpha\| > 0 \quad \text{if} \quad \sigma := \max\{\min(i_t, j_t) : 1 \leq t \leq d\} > 0.$$

If $\sigma = 0$, suppose that $\beta \in \text{Bad}$ when $\alpha = 0$. Then

$$\dim \left(\bigcap_{i=1}^d \text{Bad}(i_t, j_t) \cap L_{\alpha, \beta}\right) = 1.$$

Note that when $\sigma = 0$, we are considering the intersection of $\text{Bad}(0, 1) := \mathbb{R} \times \text{Bad}$ and/or $\text{Bad}(1, 0) := \text{Bad} \times \mathbb{R}$ with $L_{\alpha, \beta}$ and the result is essentially known. When $\alpha = 0$, the intersection of $\text{Bad}(0, 1)$ with the horizontal line $L_{0, \beta}$ given by $y = \beta$ is empty unless $\beta \in \text{Bad}$ in which case the full dimension statement is obvious. When $\alpha \neq 0$, the statement is easily verified for the intersection of $\text{Bad}(0, 1)$ or $\text{Bad}(1, 0)$ with $L_{\alpha, \beta}$. The non-trivial situation corresponds to when considering $\text{Bad}(0, 1) \cap \text{Bad}(1, 0) \cap L_{\alpha, \beta}$. The fact this intersection is uncountable is a simple consequence of Davenport’s result in [7] and it is not difficult to modify Davenport’s argument to obtain the full dimension statement.

In all likelihood Theorem 2 is best possible apart from the $\epsilon$ appearing in the Diophantine condition on the slope $\alpha$ of the line. Indeed, this is the case for vertical lines—see [4, Theorem 2]. Note that we always have that $\sigma \leq 1/2$, so Theorem 2...
is always valid for \( \alpha \in \text{Bad} \). Also we point out that as a consequence of the Jarník–Besicovitch theorem, the Hausdorff dimension of the exceptional set of \( \alpha \) for which the conclusion of the theorem is not valid is bounded above by \( 2/3 \).

\textbf{Remark 1} The proofs of Theorem 1 and Theorem 2 make use of a general Cantor framework developed in [3]. The framework is essentially extracted from the ‘raw’ construction used in [4] to establish Schmidt’s Conjecture. It will be apparent during the course of the proofs that constructing the right type of general Cantor set in the \( d = 1 \) case is the main substance. Adapting the construction to deal with finite intersections is not difficult and will follow on applying the explicit ‘finite intersection’ theorem stated in [3]. However, we point out that by utilizing the arguments in [4, §7.1] for countable intersections it is possible to adapt the \( d = 1 \) construction to obtain the following strengthening of the theorems.

\textbf{Theorem 1’} Let \((i_t, j_t)\) be a countable number of pairs of real numbers satisfying (1) and suppose that

\[
\liminf_{t \to \infty} \min\{i_t, j_t\} > 0. \tag{3}
\]

Let \( C \) be a \( C^{(2)} \) non-degenerate planar curve. Then

\[
\dim \left( \bigcap_{t=1}^{\infty} \text{Bad}(i_t, j_t) \cap C \right) = 1.
\]

\textbf{Theorem 2’} Let \((i_t, j_t)\) be a countable number of pairs of real numbers satisfying (1) and (3). Given \( \alpha, \beta \in \mathbb{R} \), let \( L_{\alpha, \beta} \) denote the line defined by the equation \( y = \alpha x + \beta \). Suppose there exists \( \epsilon > 0 \) such that

\[
\liminf_{q \to \infty} q^{1/\sigma - \epsilon} \|q\alpha\| > 0 \quad \text{where } \sigma := \sup\{\min\{i_t, j_t\} : t \in \mathbb{N}\}.
\]

Then

\[
\dim \left( \bigcap_{t=1}^{\infty} \text{Bad}(i_t, j_t) \cap L_{\alpha, \beta} \right) = 1.
\]

These statements should be true without the \( \liminf \) condition (3). Indeed, without assuming (3) the nifty argument developed by Nesharim in [10] can be exploited to show that the countable intersection of the sets under consideration are non-empty. Unfortunately, the argument fails to show positive dimension let alone full dimension.

\textbf{Remark 2} This manuscript has taken a very long time to produce. During its slow gestation, An [1] circulated a paper in which he shows that \( L_\alpha \cap \text{Bad}(i, j) \) is winning (in the sense of Schmidt games—see [13, Chp.3]) for any vertically line \( L_\alpha \) with \( \alpha \in \mathbb{R} \) satisfying the Diophantine condition \( \liminf_{q \to \infty} q^{1/i} \|q\alpha\| > 0 \). An immediate consequence of this is that \( \bigcap_{i=1}^{\infty} \text{Bad}(i_t, j_t) \cap L_\alpha \) is of full dimension as long as \( \alpha \) satisfies the Diophantine condition with \( i = \sup\{i_t : t \in \mathbb{N}\} \). The point is that this is a
statement free of (3) unlike the countable intersection result obtained in [4]. In view of An’s work it is very tempting and not at all outrageous to assert that $\text{Bad}(i, j) \cap C$ is winning at least on the part of the curve that is genuinely curved. If true this would imply Theorem 1′ without assuming (3). It is worth stressing that currently we do not even know if $\text{Bad}_2 \cap C$ is winning.

1.3 Davenport in higher dimensions: what can we expect?

For any $n$-tuple of nonnegative real numbers $i := (i_1, \ldots, i_n)$ satisfying $\sum_{s=1}^{n} i_s = 1$, denote by $\text{Bad}(i)$ the set of points $(x_1, \ldots, x_n) \in \mathbb{R}^n$ for which there exists a positive constant $c(x_1, \ldots, x_n)$ such that

$$\max\{ \|q x_1\|^{1/i_1}, \ldots, \|q x_n\|^{1/i_n}\} > c(x_1, \ldots, x_n) q^{-1} \quad \forall q \in \mathbb{N}. $$

The name of the game is to investigate the intersection of these $n$-dimensional badly approximable sets with manifolds $\mathcal{M} \subset \mathbb{R}^n$. A good starting point is to consider Davenport’s problem for arbitrary curves $C$ in $\mathbb{R}^n$. To this end and without loss of generality, we assume that $C$ is given as a graph

$$C_f := \{(f_1(x), \ldots, f_n(x)) : x \in I\}$$

where $f := (f_1, \ldots, f_n) : I \to \mathbb{R}^n$ is a map defined on an interval $I \subset \mathbb{R}$. As in the planar case, to avoid trivial empty intersection with $\text{Bad}(i)$ sets we assume that the curve is genuinely curved. A curve $C := C_f \subset \mathbb{R}^n$ is said to be $C^{(n)}$ non-degenerate if $f \in C^{(n)}(I)$ and there exists at least one point $x \in I$ such that the Wronskian

$$w(f_1', \ldots, f_n') (x) := \det(f_s^{(t)}(x))_{1 \leq s, t \leq n} \neq 0.$$

In the planar case ($n = 2$), this condition on the Wronskian is precisely the same as saying that there exits at least one point on the curve at which the curvature is non-zero. Armed with the notion of $C^{(n)}$ non-degenerate curves, there is no reason not to believe in the truth of the following statements.

**Conjecture A** Let $i := (i_{1,t}, \ldots, i_{n,t})$ be a countable number of $n$-tuples of non-negative real numbers satisfying $\sum_{t=1}^{n} i_{s,t} = 1$. Let $C \subset \mathbb{R}^n$ be a $C^{(n)}$ non-degenerate curve. Then

$$\dim \left( \bigcap_{t=1}^{\infty} \text{Bad}(i_t) \cap C \right) = 1.$$
**Conjecture B** Let $i := (i_1, \ldots, i_n)$ be an $n$-tuple of non-negative real numbers satisfying $\sum_{i=1}^{n} i_s = 1$. Let $C \subset \mathbb{R}^n$ be a $C^{(n)}$ non-degenerate curve. Then $\text{Bad}(i) \cap C$ is winning on some arc of $C$.

**Remark 3** In view of the fact that a winning set has full dimension and that the intersection of countably many winning sets is winning, it follows that Conjecture B implies Conjecture A.

**Remark 4** Conjecture A together with known results/arguments from fractal geometry implies the strongest version (arbitrary countable intersection plus full dimension) of Schmidt’s Conjecture in higher dimension:

$$\dim \left( \bigcap_{t=1}^{\infty} \text{Bad}(i_t) \right) = n.$$  

In the case $n = 2$, this follows from An’s result mentioned above (Remark 2 in Sect. 1.2)—see also his subsequent paper [2].

**Remark 5** Given that we basically know nothing in dimension $n > 2$, a finite intersection version (including the case $t = 1$) of Conjecture A would be a magnificent achievement. In all likelihood, any successful approach based on the general Cantor framework developed in [3] as in this paper would yield Conjecture A, under the extra assumption involving the natural analogue of the lim inf condition (3).

We now turn our attention to general manifolds $\mathcal{M} \subset \mathbb{R}^n$. To avoid trivial empty intersection with $\text{Bad}(i)$ sets, we assume that the manifolds under consideration are non-degenerate. Essentially, these are smooth sub-manifolds of $\mathbb{R}^n$ which are sufficiently curved so as to deviate from any hyperplane. Formally, a manifold $\mathcal{M}$ of dimension $m$ embedded in $\mathbb{R}^n$ is said to be non-degenerate if it arises from a non–degenerate map $f : U \to \mathbb{R}^n$ where $U$ is an open subset of $\mathbb{R}^m$ and $\mathcal{M} := f(U)$. The map $f : U \to \mathbb{R}^n : u \mapsto f(u) = (f_1(u), \ldots, f_n(u))$ is said to be non–degenerate at $u \in U$ if there exists some $l \in \mathbb{N}$ such that $f$ is $l$ times continuously differentiable on some sufficiently small ball centered at $u$ and the partial derivatives of $f$ at $u$ of orders up to $l$ span $\mathbb{R}^n$. If there exists at least one such non-degenerate point, we shall say that the manifold $\mathcal{M} = f(U)$ is non–degenerate. Note that in the case that the manifold is a curve $C$, this definition is absolutely consistent with that of $C$ being $C^{(n)}$ non-degenerate. Also notice, that any real, connected analytic manifold not contained in any hyperplane of $\mathbb{R}^n$ is non–degenerate. The following are the natural versions of Conjectures A & B for manifolds.

**Conjecture C** Let $i_t := (i_{1,t}, \ldots, i_{n,t})$ be a countable number of $n$-tuples of non-negative real numbers satisfying $\sum_{s=1}^{n} i_{s,t} = 1$. Let $\mathcal{M} \subset \mathbb{R}^n$ be a non-degenerate manifold. Then

$$\dim \left( \bigcap_{t=1}^{\infty} \text{Bad}(i_t) \cap \mathcal{M} \right) = \dim \mathcal{M}.$$
**Conjecture D** Let \( i := (i_1, \ldots, i_n) \) be an \( n \)-tuple of non-negative real numbers satisfying \( \sum_{i=1}^{n} i_i = 1 \). Let \( M \subset \mathbb{R}^n \) be a non-degenerate manifold. Then \( \text{Bad}(i) \cap M \) is winning on some patch of \( M \).

**Remark 6** Conjecture A together with the fibering technique of Pyartly [12] should establish Conjecture C for non-degenerate manifolds that can be foliated by non-degenerate curves. In particular, this includes any non-degenerate analytic manifold.\(^2\)

Beyond manifolds, it would be desirable to investigate Davenport’s problem within the more general context of friendly measures [9]. We suspect that the above conjectures for manifolds remain valid with \( M \) replaced by a subset \( X \) of \( \mathbb{R}^n \) that supports a friendly measure.

### 2 Preliminaries

Concentrating on Theorem 1, since any subset of a planar curve \( C \) is of dimension less than or equal to one we immediately obtain that

\[
\dim \left( \bigcap_{d \leq 1} \text{Bad}(i_j \in J) \cap C \right) \leq 1. \tag{4}
\]

Thus, the proof of Theorem 1 reduces to establishing the complementary lower bound statement and as already mentioned in Sect. 1 (Remark 1) the crux is the \( d = 1 \) case. Without loss of generality, we assume that \( i \leq j \). Also, the case that \( i = 0 \) is relatively straightforward to handle so let us assume that

\[
0 < i < j < 1 \quad \text{and} \quad i + j = 1, \tag{5}
\]

Then, formally the key to establishing Theorem 1 is the following statement.

**Theorem 3** Let \( (i, j) \) be a pair of real numbers satisfying (5). Let \( C \) be a \( C^{(2)} \) non-degenerate planar curve. Then

\[
\dim \text{Bad}(i, j) \cap C \geq 1.
\]

The hypothesis that \( C = C_f := \{(x, f(x)) : x \in I\} \) is \( C^{(2)} \) non-degenerate implies that there exist positive constants \( C_0, c_0 > 0 \) so that

\[
c_0 \leq |f'(x)| < C_0 \quad \text{and} \quad c_0 \leq |f''(x)| < C_0 \quad \forall \ x \in I. \tag{6}
\]

\(^2\) A few days before completing this paper, Victor Beresnevich communicated to us that he has established Conjecture A under the extra assumption involving the natural analogue of (3). In turn, under this assumption, by making use of Pyartly’s technique he has proved Conjecture C for non-degenerate analytic manifolds. This in our opinion represents a magnificent achievement—see Remark 5.

**Added in proof:** V. Beresnevich: **Badly approximable points on manifolds.** Pre-print: arXiv:1304.0571.
To be precise, in general we can only guarantee (6) on a sufficiently small sub-interval $I_0$ of $I$. Nevertheless, establishing Theorem 3 for the ‘shorter’ curve $C_f^* = \{(x, f(x)) : x \in I_0\}$ corresponding to $f$ restricted to $I_0$ clearly implies the desired dimension result for the curve $C_f$.

To simplify notation the Vinogradov symbols $\ll$ and $\gg$ will be used to indicate an inequality with an unspecified positive multiplicative constant. Unless stated otherwise, the unspecified constant will at most be dependant on $i, j, C_0$ and $c_0$ only. If $a \ll b$ and $a \gg b$ we write $a \asymp b$, and say that the quantities $a$ and $b$ are comparable.

2.1 Geometric interpretation of $\text{Bad}(i, j) \cap C$

We will work with the dual form of $\text{Bad}(i, j)$ consisting of points $(x, y) \in \mathbb{R}^2$ satisfying (2). In particular, for any constant $c > 0$, let $\text{Bad}_c(i, j)$ denote the set of points $(x, y) \in \mathbb{R}^2$ such that

$$\max\{|A|^{1/i}, |B|^{1/j}\} \|Ax - By\| > c \quad \forall (A, B) \in \mathbb{Z}^2\setminus\{(0, 0)\}. \quad (7)$$

It is easily seen that $\text{Bad}_c(i, j) \subset \text{Bad}(i, j)$ and

$$\text{Bad}(i, j) = \bigcup_{c>0} \text{Bad}_c(i, j).$$

Geometrically, given integers $A, B, C$ with $(A, B) \neq (0, 0)$ consider the line $L = L(A, B, C)$ defined by the equation

$$Ax - By + C = 0.$$ 

The set $\text{Bad}_c(i, j)$ simply consists of points in the plane that avoid the

$$\frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\} \sqrt{A^2 + B^2}}$$

thickening of each line $L$—alternatively, points in the plane that lie within any such neighbourhood are removed. A consequence of (6) is that this thickening intersects $\mathcal{C}$ in at most two closed arcs. Either of these arcs will be denoted by $\Delta(L)$. Let $\mathcal{R}_0$ be the collection of arcs $\Delta(L)$ on $\mathcal{C}$ arising from lines $L = L(A, B, C)$ with integer coefficients and $(A, B) \neq (0, 0)$.

The upshot of the above analysis is that the set $\text{Bad}_c(i, j) \cap \mathcal{C}$ can be described as the set of all points on $\mathcal{C}$ that survive after removing the arcs $\Delta(L) \in \mathcal{R}_0$. Formally,

$$\text{Bad}_c(i, j) \cap \mathcal{C} = \{(x, f(x)) \in \mathcal{C} : (x, f(x)) \notin \Delta(L) \quad \forall \Delta(L) \in \mathcal{R}_0\}.$$ 

For reasons that will become apparent later, it will be convenient to remove all but finitely many arcs. With this in mind, let $\mathcal{S}$ be a finite sub-collection of $\mathcal{R}_0$ and consider the set
\[
\text{Bad}_{c,S}(i, j) \cap \mathcal{C} = \{(x, f(x)) \in \mathcal{C} : (x, f(x)) \notin \Delta(L) \quad \forall \Delta(L) \in \mathcal{R}_0 \setminus S\}.
\]

Clearly, since we are removing fewer arcs \( \text{Bad}_{c,S}(i, j) \supset \text{Bad}_{c}(i, j) \). On the other hand,

\[
S := \{(x, f(x)) \in \mathcal{C} : Ax - Bf(x) + C = 0 \text{ for some } L(A, B, C) \text{ with } \Delta(L) \in S\}
\]

is a finite set of points and it is easily verified that

\[
\text{Bad}_{c,S}(i, j) \cap \mathcal{C} \subset (\text{Bad}_{c}(i, j) \cap \mathcal{C}) \cup S.
\]

Since \( \dim S = 0 \) for any finite set \( S \) of points, Theorem 3 will follow on showing that

\[
\dim \text{Bad}_{c,S}(i, j) \cap \mathcal{C} \to 1 \quad \text{as} \quad c \to 0.
\] (8)

In Sect. 2.2.1 we will specify exactly the finite collection of arcs \( S \) that are not to be removed and put \( \mathcal{R} := \mathcal{R}_0 \setminus S \) for this choice of \( S \).

Remark 7 Without loss of generality, when considering lines \( L = L(A, B, C) \) we will assume that

\[
(A, B, C) = 1.
\]

Otherwise we can divide the coefficients of \( L \) by their common divisor. Then the resulting line \( L' \) will satisfy the required conditions and moreover \( \Delta(L') \supseteq \Delta(L) \). Therefore, removing the arc \( \Delta(L') \) from \( \mathcal{C} \) takes care of removing \( \Delta(L) \).

2.1.1 Working with the projection of \( \text{Bad}_{c,S}(i, j) \cap \mathcal{C} \)

Recall that \( \mathcal{C} = \mathcal{C}_f := \{(x, f(x)) : x \in I\} \) where \( I \subset \mathbb{R} \) is an interval. Let \( \text{Bad}_{c,S}^f(i, j) \) denote the set of \( x \in I \) such that \((x, f(x)) \in \text{Bad}_{c,S}(i, j) \cap \mathcal{C} \). In other words \( \text{Bad}_{c,S}^f(i, j) \) is the orthogonal projection of \( \text{Bad}_{c,S}(i, j) \cap \mathcal{C} \) onto the \( x \)-axis. Now notice that in view of (6) the function \( f \) is Lipschitz; i.e. for some \( \lambda > 1 \)

\[
|f(x) - f(x')| \leq \lambda |x - x'| \quad \forall x, x' \in I.
\]

Thus, the sets \( \text{Bad}_{c,S}^f(i, j) \) and \( \text{Bad}_{c,S}(i, j) \cap \mathcal{C} \) are related by a bi-Lipschitz map and so

\[
\dim \text{Bad}_{c,S}(i, j) \cap \mathcal{C} = \dim \text{Bad}_{c,S}^f(i, j).
\]

Hence establishing (8) is equivalent to showing that

\[
\dim \text{Bad}_{c,S}^f(i, j) \to 1 \quad \text{as} \quad c \to 0.
\] (9)

Next observe that \( \text{Bad}_{c,S}^f(i, j) \) can equivalently be written as the set of \( x \in I \) such that \( x \notin \Pi(\Delta(L)) \) for all \( \Delta(L) \in \mathcal{R}_0 \setminus S \) where the interval \( \Pi(\Delta(L)) \subset I \) is the
Badly approximable points on planar curves and a problem of Davenport

orthogonal projection of the arc $\Delta(L) \subseteq \mathcal{C}$ onto the $x$-axis. Throughout the paper, we use the fact that the sets under consideration can be viewed either in terms of arcs $\Delta(L)$ on the curve $\mathcal{C}$ or sub-intervals $\Pi(\Delta(L))$ of $I$. In order to minimize unnecessary and cumbersome notation, we will simply write $\Delta(L)$ even in the case of intervals and always refer to $\Delta(L)$ as an interval. It will be clear from the context whether $\Delta(L)$ is an arc on a curve or a genuine interval on $\mathbb{R}$. However, we stress that by the length of $\Delta(L)$ we will always mean the length of the interval $\Pi(\Delta(L))$. In other words,

$$|\Delta(L)| := |\Pi(\Delta(L))|.$$

2.2 An estimate for the size of $\Delta(L)$

Given a line $L = L(A, B, C)$, consider the function

$$F_L : I \to \mathbb{R} : x \to F_L(x) := Ax - Bf(x) + C.$$  

To simplify notation, if there is no risk of ambiguity we shall simply write $F(x)$ for $F_L(x)$. Now given an interval $\Delta(L) = \Delta(L(A, B, C))$ let

$$V_L(\Delta) := \min_{x \in \Delta(L)} \{|F'_L(x)|\} = \min_{x \in \Delta(L)} \{|A - Bf'(x)|\}.$$  

Since $\Delta(L)$ is closed and $F_L$ is continuous the minimum always exists. If there is no risk of ambiguity we shall simply write $V_L$ for $V_L(\Delta)$. In short, the quantity $V_L$ plays a crucial role in estimating the size of $\Delta(L)$.

**Lemma 1** There exists an absolute constant $K \geq 1$ dependent only on $i, j, C_0$ and $c_0$ such that

$$|\Delta(L)| \leq K \min \left\{ c \left( \frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\} \cdot V_L} \right)^{1/2} \right\}. \quad (10)$$

**Proof** The statement is essentially a consequence of Pyartly’s Lemma [12]: Let $\delta, \mu > 0$ and $I \subseteq \mathbb{R}$ be some interval. Let $f(x) \in C^n(I)$ be function such that $|f^{(n)}(x)| > \delta$ for all $x \in I$. Then there exists a constant $c(n)$ such that

$$|[x \in I : |f(x)| < \mu]| \leq c(n) \left( \frac{\mu}{\delta} \right)^{1/n}.$$

Armed with this, the first estimate for $|\Delta(L)|$ follows from the fact that

$$|F'_L(x)| \geq \delta := V_L \quad \text{and} \quad |F_L(x)| \leq \mu := \frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\}}$$

for all $x \in \Delta(L)$. The second makes use of the fact that

$$|F''_L(x)| = |Bf''(x)| > c_0|B| \quad \forall x \in \Delta(L).$$

□
Remark 8 The second term inside the minimum on the r.h.s. of (10) is absolutely crucial. It shows that the length of $\Delta(L)$ can not be arbitrary large even when the quantity $V_L$ is small or even equal to zero. The second term is not guaranteed if the curve is degenerate. However, for the lines (degenerate curves) $L_{\alpha, \beta}$ considered in Theorem 2 the Diophantine condition on $\alpha$ guarantees that $V_L$ is not too small and hence allows us to adapt the proof of Theorem 3 to this degenerate situation.

2.2.1 Type 1 and Type 2 intervals

Consider an interval $\Delta(L) = \Delta(L(A, B, C)) \in \mathcal{R}$. Then Lemma 1 implies that

$$\Delta(L) \subseteq \Delta_1^*(L) \quad \text{and} \quad \Delta(L) \subseteq \Delta_2^*(L),$$

where the intervals $\Delta_1^*(L)$ and $\Delta_2^*(L)$ have the same center as $\Delta(L)$ and length given by

$$|\Delta_1^*(L)| := \frac{2K \cdot c}{\max\{|A|^{1/i}, |B|^{1/j}\} \cdot V_L},$$

$$|\Delta_2^*(L)| := 2K \left(\frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\} \cdot |B|}\right)^{1/2}.$$

We say that the interval $\Delta_1^*(L)$ is of Type 1 and $\Delta_2^*(L)$ is of Type 2. For obvious reasons, we assume that $B \neq 0$ in the case of Type 2. For each type of interval we define its height in the following way:

$$H(\Delta_1^*) = H(A, B) := c^{-1/2} \cdot V_L \cdot \max\{|A|^{1/i}, |B|^{1/j}\};$$

$$H(\Delta_2^*) = H(A, B) := (\max\{|A|^{1/i}, |B|^{1/j}\} \cdot |B|)^{1/2}.$$

So if $\Delta^*(L)$ denotes an interval of either type we have that

$$|\Delta^*(L)| = 2Ke^{1/2} \cdot (H(\Delta^*))^{-1}.$$

Remark 9 Notice that for each positive number $H_0$ there are only finitely many intervals $\Delta_2^*(L)$ of Type 2 such that $H(\Delta_2^*) \leq H_0$.

Recall, geometrically $\text{Bad}_{c, S}(i, j) \cap \mathcal{C}$ (resp. its projection $\text{Bad}_{c, S}^f(i, j)$) is the set of points on $\mathcal{C}$ (resp. $I$) that survive after removing the intervals $\Delta(L) \in \mathcal{R}_0 \setminus S$. We now consider the corresponding subsets obtained by removing the larger intervals $\Delta^*(L)$. Given $\Delta(L) \in \mathcal{R}_0$, the criteria for which type of interval $\Delta^*(L)$ represents is as follows. Let $R \geq 2$ be a large integer and $\lambda$ be a constant satisfying

$$\lambda > \max\left\{4, \frac{1}{i}, \frac{1+i}{j}\right\}. \quad (11)$$

Furthermore, assume that the constant $c > 0$ satisfies

$$c < \min\left\{(8(C_0 + 1)R^{-1-ij/2-\lambda})^2, ((C_0 + 1)C_0R^2)^{-2}\right\}. \quad (12)$$
Given $\Delta(L)$ consider the associated Type 1 interval $\Delta^*_1(L)$. There exists a unique $d \in \mathbb{Z}$ such that
\[ R^d \leq H(\Delta^*_1) < R^{d+1}. \quad (13) \]
Choose $l_0$ to be the largest integer such that
\[ \lambda l_0 \leq \max\{d, 0\}. \quad (14) \]
Then we choose $\Delta^*(L)$ to be the interval $\Delta^*_1(L)$ of Type 1 if
\[ V_L > (C_0 + 1)R^{-\lambda(l_0+1)} \max\{|A|, |B|\}. \]
Otherwise, we take $\Delta^*(L)$ to be the interval $\Delta^*_2(L)$ of Type 2. Formally
\[ \Delta^*(L) := \begin{cases} \Delta^*_1(L) & \text{if } V_L > (C_0 + 1)R^{-\lambda(l_0+1)} \max\{|A|, |B|\} \\ \Delta^*_2(L) & \text{otherwise.} \end{cases} \quad (15) \]

**Remark 10** It is easily verified that for either type of interval, we have that
\[ H(\Delta^*) \geq 1. \]
For Type 2 intervals $\Delta^*_2(L)$ this follows by definition. For Type 1 intervals $\Delta^*_1(L)$ assume that $H(\Delta_1) < 1$. It then follows that $d < 0$ and $l_0 = 0$. In turn this implies that
\[ H(\Delta_1) := c^{-1/2}V_L \max\{|A|^{1/i}, |B|^{1/j}\} \]
\[ \geq c^{-1/2}(C_0 + 1)R^{-\lambda} \max\{|A|, |B|\} \max\{|A|^{1/i}, |B|^{1/j}\} \]
\[ \geq \max\{|A|, |B|\} \max\{|A|^{1/i}, |B|^{1/j}\} \geq 1. \quad (12) \]
This contradicts our assumption and thus we must have that $H(\Delta_1) \geq 1$.

We now specify the finite sub-collection $S$ of intervals from $R_0$ which are not to be removed. Let $n_0 = n_0(c, R)$ be the minimal positive integer satisfying
\[ c^{1/2} \cdot R^{n_0} \cdot C_0 \geq 1. \quad (16) \]
Then, define $S$ to be the collection of intervals $\Delta(L) \in R_0$ so that $\Delta^*(L)$ is of Type 2 and $H(\Delta^*) < R^{3n_0}$. Clearly $S$ is a finite collection of intervals—see Remark 9 above. For this particular collection $S$ we put
\[ R := R_0 \setminus S. \]

Armed with this criteria for choosing $\Delta^*(L)$ given $\Delta(L)$ and indeed the finite collection $S$ we consider the set
\[ \text{Bad}^*_c(i, j) \cap C := \{(x, f(x)) \in C : (x, f(x)) \cap \Delta^*(L) = \emptyset \ \forall \ \Delta(L) \in R\}. \quad (17) \]
Clearly,

\[
\text{Bad}_c(i, j) \cap C \subset \text{Bad}_{c, S}(i, j) \cap C
\]

and so Theorem 3 will follow on showing (8) with \(\text{Bad}_{c, S}(i, j) \cap C\) replaced by \(\text{Bad}_c(i, j) \cap C\). Indeed, from this point onward we will work with set defined by (17). In view of this and to simplify notation we shall simply redefine \(\text{Bad}_c(i, j) \cap C\) to be \(\text{Bad}_c(i, j) \cap C\) and write \(\Delta_1(L)\) for \(\Delta_1^*(L)\). Just to make it absolutely clear, the intervals \(\Delta_1(L) := \Delta_1^*(L)\) are determined via the criteria (15) and \(R\) is the collection of such intervals arising from lines \(L = L(A, B, C)\) apart from those associated with \(S\). Also, the set \(\text{Bad}_c^*(i, j) \cap C := \text{Bad}_c(i, j) \cap C\). With this in mind, the key to establishing (9), which in turn implies (8) and therefore Theorem 3, lies in constructing a Cantor-type subset \(K_c(i, j)\) of \(\text{Bad}_c(i, j)\) such that

\[
\dim K_c(i, j) \to 1 \quad \text{as} \quad c \to 0.
\]

3 Cantor sets and applications

The proof of Theorem 1 and indeed Theorem 2 makes use of a general Cantor framework developed in [3]. This is what we now describe.

3.1 A general Cantor framework

The parameters. Let \(I\) be a closed interval in \(\mathbb{R}\). Let

\[
R := (R_n) \quad \text{with} \quad n \in \mathbb{Z}_{\geq 0}
\]

be a sequence of natural numbers and

\[
r := (r_{m,n}) \quad \text{with} \quad m, n \in \mathbb{Z}_{\geq 0} \quad \text{and} \quad m \leq n
\]

be a two parameter sequence of non-negative real numbers.

The construction. We start by subdividing the interval \(I\) into \(R_0\) closed intervals \(I_1\) of equal length and denote by \(I_1\) the collection of such intervals. Thus,

\[
\#I_1 = R_0 \quad \text{and} \quad |I_1| = R_0^{-1} |I|.
\]

Next, we remove at most \(r_{0,0}\) intervals \(I_1\) from \(I_1\). Note that we do not specify which intervals should be removed but just give an upper bound on the number of intervals to be removed. Denote by \(J_1\) the resulting collection. Thus,

\[
\#J_1 \geq \#I_1 - r_{0,0}.
\]
For obvious reasons, intervals in \( J_1 \) will be referred to as (level one) survivors. It will be convenient to define \( J_0 := \{ J_0 \} \) with \( J_0 := 1 \).

In general, for \( n \geq 0 \), given a collection \( J_n \) we construct a nested collection \( J_{n+1} \) of closed intervals \( J_{n+1} \) using the following two operations.

- **Splitting procedure.** We subdivide each interval \( J_n \in J_n \) into \( R_n \) closed sub-intervals \( I_{n+1} \) of equal length and denote by \( T_{n+1} \) the collection of such intervals. Thus,

\[
\# T_{n+1} = R_n \times \# J_n \quad \text{and} \quad |I_{n+1}| = R_n^{-1} |J_n|.
\]

- **Removing procedure.** For each interval \( J_n \in J_n \) we remove at most \( r_n \) intervals \( I_{n+1} \in T_{n+1} \) that lie within \( J_n \). Note that the number of intervals \( I_{n+1} \) removed is allowed to vary amongst the intervals in \( J_n \). Let \( T_{n+1}^{n+1} \subseteq T_{n+1} \) be the collection of intervals that remain. Next, for each interval \( J_{n-k} \in J_{n-k} \) we remove at most \( r_{n-k} \) intervals \( I_{n+1} \in T_{n+1} \) that lie within \( J_{n-k} \). Also we let \( T_{n+1}^{n-k} \subseteq T_{n+1}^{n-k+1} \) be the collection of intervals that remain. In particular, \( J_{n+1} := T_{n+1}^{0} \) is the desired collection of (level \( n+1 \)) survivors. Thus, the total number of intervals \( I_{n+1} \) removed during the removal procedure is at most \( r_{n} \# J_{n} + r_{n-1} \# J_{n-1} + \cdots + r_{0} \# J_{0} \) and so

\[
\# J_{n+1} \geq R_n \# J_n - \sum_{k=0}^{n} r_{k-n} \# J_k.
\] (19)

Finally, having constructed the nested collections \( J_n \) of closed intervals we consider the limit set

\[ K(I, R, r) := \bigcap_{n=1}^{\infty} \bigcup_{J \in J_n} J. \]

The set \( K(I, R, r) \) will be referred to as a \((I, R, r)\) Cantor set. For further details and examples see [3, §2.2]. The following result ([3, Theorem 4] enables us to estimate the Hausdorff dimension of \( K(I, R, r) \). It is the key to establishing Theorem 1.

**Theorem 4** Given \( K(I, R, r) \), suppose that \( R_n \geq 4 \) for all \( n \in \mathbb{Z}_{\geq 0} \) and that

\[
\sum_{k=0}^{n} \left( r_{n-k} \prod_{i=1}^{k} \left( \frac{4}{R_{n-i}} \right) \right) \leq \frac{R_n}{4}. \] (20)

Then

\[ \dim K(I, R, r) \geq \liminf_{n \to \infty} (1 - \log_{R_n} 2). \]
Here we use the convention that the product term in \((20)\) is one when \(k = 0\) and by definition \(\log_{R_n} 2 := \log 2 / \log R_n\).

The next result [3, Theorem 5] enables us to show that the intersection of finitely many sets \(\mathcal{K}(I, R, r_i)\) is yet another \((I, R, r)\) Cantor set for some appropriately chosen \(r\). This will enable us to establish Theorem 1.

**Theorem 5**  For each integer \(1 \leq i \leq k\), suppose we are given a set \(\mathcal{K}(I, R, r_i)\). Then

\[
\bigcap_{i=1}^{k} \mathcal{K}(I, R, r_i)
\]

is a \((I, R, r)\) Cantor set where

\[
r := (r_{m,n}) \quad \text{with} \quad r_{m,n} := \sum_{i=1}^{k} r_{m,n}^{(i)}.
\]

### 3.2 The applications

We wish to construct an appropriate Cantor-type set \(K_c(i, j) \subset \text{Bad}_c^f(i, j)\) which fits within the general Cantor framework of Sect. 3.1. With this in mind, let \(R \geq 2\) be a large integer and

\[
c_1 := c^{\frac{1}{2}} R^{1+\omega} \quad \text{where} \quad \omega := \frac{ij}{4}
\]

and the constant \(c > 0\) satisfies \((12)\). Take an interval \(J_0 \subset I\) of length \(c_1\). With reference to Sect. 3.1 we denote by \(J_0 := \{J_0\}\). We establish, by induction on \(n\), the existence of the collection \(J_n\) of closed intervals \(J_n\) such that \(J_n\) is nested in \(J_{n-1}\); that is, each interval \(J_n\) in \(J_n\) is contained in some interval \(J_{n-1}\) in \(J_{n-1}\). The length of an interval \(J_n\) will be given by

\[
|J_n| := c_1 R^{-n},
\]

and each interval \(J_n\) will satisfy the condition

\[
J_n \cap \Delta(L) = \emptyset \quad \forall \ L \ \text{with} \ H(\Delta) < R^{n-1}.
\]

(21)

In particular we put

\[
K_c(i, j) := \bigcap_{n=1}^{\infty} \bigcup_{J \in J_n} J
\]

By construction, we have that

\[
K_c(i, j) \subset \text{Bad}^f_c(i, j)
\]
Now let
\[ \epsilon := \frac{ijw}{2} = \frac{(ij)^2}{8} \quad \text{and} \quad R > R_0(\epsilon) \]
be sufficiently large. Recall that we are assuming that \( j \geq i > 0 \) and so \( \epsilon \) is strictly positive—we deal with the \( i = 0 \) case later in Sect. 5.1. Let \( n_0 = n_0(c, R) \) be the minimal positive integer satisfying (16); i.e.
\[ c^{1/2} \cdot R^{n_0} \cdot C_0 \geq 1. \]

It will be apparent from the construction of the collections of \( J_n \) described in Sect. 5 that \( K_c(i, j) \) is in fact a \((J_0, R, r)\) Cantor set \( \mathcal{K}(J_0, R, r) \) with
\[ R := (R_n) = (R, R, R, \ldots) \]
and
\[ r := (r_{m,n}) = \begin{cases} 4R_{1-\epsilon}^{1-\epsilon} & \text{if } m = n; \\ 2R_{1-\epsilon}^{1-\epsilon} & \text{if } m < n, \ n - m \neq n_0 \\ 3R_{1-\epsilon}^{1-\epsilon} & \text{if } n - m = n_0, \ n \geq 3n_0 \end{cases} \]

By definition, note that for \( R > R_0(\epsilon) \) large enough we have that
\[ \text{l.h.s. of (20)} = \sum_{k=0}^{n} r_{n-k,n} \left( \frac{4}{R} \right)^k \leq 4R_{1-\epsilon}^{1-\epsilon} \frac{1}{1 - 4/R} \leq \frac{R}{4} = \text{r.h.s. of (20)}. \]

Also note that \( R_n \geq 4 \) for \( R \) large enough. Then it follows via Theorem 4 that
\[ \dim \BAD_c^f(i, j) \geq \dim K_c(i, j) = \dim \mathcal{K}(J_0, R, r) \geq 1 - \log_2 R. \]

This is true for all \( R \) large enough (equivalently all \( c > 0 \) small enough) and so on letting \( R \to \infty \) we obtain that
\[ \dim \BAD(i, j) \cap C \geq \dim \BAD_c^f(i, j) \to 1. \]

This proves Theorem 3 modulo the construction of the collections \( J_n \) and dealing with \( i = 0 \). Moreover, Theorem 5 implies that
\[ \bigcap_{t=1}^{d} \BAD(i_t, j_t) \cap C \]
contains the Cantor-type set $\mathcal{K}(J_0, R, \tilde{r})$ with

$$\tilde{r} := (\tilde{r}_{m, n}) = \begin{cases} 4dR^{1-\tilde{\epsilon}} & \text{if } m = n; \\ 2dR^{1-\tilde{\epsilon}} & \text{if } m < n, \ n - m \neq n_0 \\ 3dR^{1-\tilde{\epsilon}} & \text{if } n - m = n_0, \ n \geq 3n_0, \end{cases}$$

where

$$\tilde{\epsilon} := \min_{1 \leq t \leq d} \left( \frac{(i_t j_t)^2}{8} \right).$$

On applying Theorem 4 to the set $\mathcal{K}(J_0, R, \tilde{r})$ and letting $R \to \infty$ implies that

$$\dim \left( \bigcap_{t=1}^{d} \text{Bad}(i_t, j_t) \cap C \right) \geq 1.$$  

This together with the upper bound statement (4) establishes Theorem 1 modulo of course the construction of the collections $J_n$ and the assumption that $i > 0$.

### 4 Preliminaries for constructing $J_n$

In order to construct the appropriate collections $J_n$ described in Sect. 3.2, it is necessary to partition the collection $\mathcal{R}$ of intervals $\Delta(L)$ into various classes. The aim is to have sufficiently good control on the parameters $|A|, |B|$ and $V_L$ within each class. Throughout, $R \geq 2$ is a large integer.

- Firstly we partition all Type 1 intervals $\Delta(L) \in \mathcal{R}$ into classes $C(n)$ and $C(n, k, l)$.

  A Type 1 interval $\Delta(L) \in C(n)$ if

  $$R^{n-1} \leq H(\Delta) < R^n. \quad (22)$$

Furthermore, $\Delta(L) \in C(n, k, l) \subset C(n)$ if

$$2^k R^{n-1} \leq H(\Delta) < 2^{k+1} R^{n-1} \quad 0 \leq k < \log_2 R, \quad (23)$$

$$R^{-\lambda(l+1)}(C_0 + 1) \max\{|A|, |B|\} < V_L \leq R^{-\lambda l}(C_0 + 1) \max\{|A|, |B|\}. \quad (24)$$

and $\Delta(L) \not\in \Delta(L')$ for any previous $\Delta(L') \in C(n', k', l')$ with $(n', k') < (n, k)$. Here by $(n', k') < (n, k)$ we mean either $n' < n$ or $n' = n$ and $k' < k$.

Note that since the intervals $\Delta(L)$ are of Type 1, it follows from (14) that $l \leq l_0$. Moreover

$$V_L = |A - Bf'(x_0)| \leq |A| + C_0|B| \leq (1 + C_0) \max\{|A|, |B|\} \quad (6)$$
so \( l \) is also nonnegative. Here and throughout \( x_0 \) is the point at which \(|F'_L(x)| = |A - Bf'(x)|\) attains its minimum with \( x \in \Delta(L) \). We let

\[
C(n, l) := \bigcup_{k=0}^{\log_2 R} C(n, k, l).
\]

- Secondly we partition all Type 2 intervals \( \Delta(L) \in \mathcal{R} \) into classes \( C^*(n) \) and \( C^*(n, k) \).

A Type 2 interval \( \Delta(L) \in C^*(n) \) if (22) is satisfied. Furthermore, \( \Delta(L) \in C^*(n, k) \subset C^*(n) \) if (23) is satisfied and also \( \Delta(L) \not\subset \Delta(L') \) for any previous \( \Delta(L') \in C^*(n', k') \) with \( (n', k') < (n, k) \).

Note that since \( H(\Delta) \geq 1 \), we have the following the complete split of \( \mathcal{R} \):

\[
\mathcal{R} = \left( \bigcup_{n=0}^{\infty} C(n) \right) \cup \left( \bigcup_{n=0}^{\infty} C^*(n) \right).
\]

We now investigate the consequences of the above classes on the parameters \(|A|, |B|\)

and \( V_L \) and introduce further subclasses to gain tighter control.

4.1 Estimates for \(|A|, |B|\) and \( V_L \) within a given class

4.1.1 Class \( C(n, k, l) \) with \( l \geq 1 \)

Suppose \( \Delta(L(A, B, C)) \in C(n, k, l) \) for some \( l \geq 1 \). By definition each of these classes corresponds to the case that the derivative \( V_L = |F'_L(x_0)| \) satisfies (24). In other words the derivative is essentially smaller than the expected value \( \max\{|A|, |B|\} \).

Now observe that the r.h.s. of (24) implies either

\[
|A - f'(x_0)B| < \frac{C_0 + 1}{R^\lambda} |A| \Leftrightarrow \left( 1 - \frac{C_0 + 1}{R^\lambda} \right) < \frac{|f'(x_0)B|}{|A|} < \left( 1 + \frac{C_0 + 1}{R^\lambda} \right)
\]

or

\[
|A - f'(x_0)B| < \frac{C_0 + 1}{R^\lambda} |B| \Leftrightarrow \left( 1 - \frac{C_0 + 1}{R^\lambda} \right) < \frac{|A|}{|f'(x_0)B|} < \left( 1 + \frac{C_0 + 1}{|f'(x_0)|R^\lambda} \right).
\]

Since \( |f'(x_0)| \geq c_0 > 0 \) then in both cases, for \( R \) large enough we have that

\[
2^{-1} |A| < |f'(x_0)B| < 2|A| \quad \text{or} \quad |A| \asymp |B|.
\]

On substituting the estimate (24) for \( V_L \) into the definition of the height \( H(\Delta) \) we obtain that

\[
c^{-\frac{1}{2}} \cdot |A|^{\max\left\{ \frac{i+1}{r}, \frac{i+1}{j} \right\}} R^{-\lambda(j+1)} \ll H(\Delta) \ll c^{-\frac{1}{2}} \cdot |A|^{\max\left\{ \frac{i+1}{r}, \frac{i+1}{j} \right\}} R^{-\lambda j}.
\]
This together with (23) and the fact that \( i \leq j \), implies that

\[
\left( \frac{2^k c \frac{1}{2}}{R} R^{n+\lambda} \right)^{\frac{i}{i+1}} \ll |A|, |B| \ll \left( \frac{2^k c \frac{1}{2}}{R} R^{n+\lambda(l+1)} \right)^{\frac{i}{i+1}}. \tag{26}
\]

### 4.1.2 Class C(\( n, k, 0 \))

By (23) and (24), we have that in this case

\[
c^{-\frac{1}{2}} \cdot \frac{\max\{|A|, |B|\}}{R^{\lambda}} \max\{|A|^{1/i}, |B|^{1/j}\} \ll H(\Delta) \ll \frac{2^k}{R} R^n.
\]

Therefore,

\[
|A| \ll \left( \frac{2^k c \frac{1}{2}}{R} R^{n+\lambda} \right)^{\frac{i}{i+1}}, \tag{27}
\]

\[
|B| \ll \left( \frac{2^k c \frac{1}{2}}{R} R^{n+\lambda} \right)^{\frac{j}{j+1}}. \tag{28}
\]

Unfortunately these bounds for \( |A| \) and \( |B| \) are not strong enough for our purpose. Thus, we partition the class \( C(n, k, 0) \) into the following subclasses:

- **Subclass** \( C_1(n, k) \) of \( C(n, k, 0) \). By (27) we have the following bounds for \( |B| \) and \( V_L \):

\[
|B|, V_L \ll \left( \frac{2^k c \frac{1}{2}}{R} R^{n+\lambda} \right)^{\frac{i}{i+1}}. \tag{29}
\]

Note that this bound for \( |B| \) is stronger than (28).

- **Subclass** \( C_2(n, k) \) of \( C(n, k, 0) \). We can strengthen the bound (27) for \( |A| \) by the following:

\[
|A| \leq |B|^{i/j} \ll \left( \frac{2^k c \frac{1}{2}}{R} R^{n+\lambda} \right)^{\frac{i}{i+1}}. \tag{30}
\]

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Since $|A| < \frac{1}{2} |f'(x_0)||B|$ we have that $V_L \asymp |B|$, therefore

$$V_L \ll \left( \frac{2^k c^\frac{1}{2}}{R} R^{n+\lambda} \right)^{\frac{j}{j+\frac{1}{2}}}.$$  \hspace{1cm} (31)

Also we get that $\max\{|A|^{1/i}, |B|^{1/j}\} = |B|^{1/j}$ which together with (23) implies that for any two $\Delta(L_1(A_1, B_1, C_1)), \Delta(L_2(A_2, B_2, C_2)) \in C_2(n, k)$,

$$V_{L_1} \asymp B_1 \asymp B_2 \asymp V_{L_2}. \hspace{1cm} (32)$$

- **Subclass** $C_3(n, k)$ of $C(n, k, 0)$. As with the previous subclass $C_2(n, k)$ we have that

$$V_L \asymp |B| \hspace{0.5cm} \forall \hspace{0.5cm} \Delta(L(A_2, B_2, C_2)) \in C_3(n, k).$$

We partition $C_3(n, k)$ into subclasses $C_3(n, k, u, v)$ consisting of intervals $\Delta(L(A, B, C)) \in C_3(n, k)$ with

$$2^u R^{\lambda u} |B|^{1/j} < |A|^{1/i} \leq 2^{u+1} R^{\lambda u} |B|^{1/j} \quad u \geq 0 \quad \lambda \log_2 R \geq v \geq 0. \hspace{1cm} (33)$$

Then

$$|B|^{\frac{i+1}{j}} R^{\lambda u} < |B||A|^{1/i} \asymp V_L \max\{|A|^{1/i}, |B|^{1/j}\} = c^\frac{1}{2} H(\Delta) \leq \frac{2^{k+1} c^\frac{1}{2}}{R} R^n. \hspace{1cm} (34)$$

Therefore

$$V_L \asymp |B| \ll \left( \frac{2^k c^\frac{1}{2}}{R} R^n \right)^{\frac{j}{j+\frac{1}{2}}} R^{-\frac{\lambda u i}{j+\frac{1}{2}}} \hspace{1cm} (34)$$

and

$$|A| \ll R^{\lambda (u+1)i} |B|^{i/j} \ll \left( \frac{2^k c^\frac{1}{2}}{R} R^n \right)^{\frac{j}{j+\frac{1}{2}}} R^{\frac{\lambda u i j}{j+\frac{1}{2}}} \hspace{1cm} (35)$$

We proceed with estimating the size of the parameter $u$. The fact that $|A| < \frac{1}{2} |f'(x_0)||B|$ together with (33) and (34) implies that

$$R^{\lambda u} \leq \frac{|A|^{1/i}}{|B|^{1/j}} \ll |B|^{\frac{i-1}{ij}} \ll R^{\frac{(j-i)n}{(j+1)}}. \hspace{1cm} (34)$$

Therefore for large $R$, if $C_3(n, k, u, v)$ is nonempty then $u$ satisfies

$$0 \leq \lambda u \leq \frac{j - i}{i(1 + j)} \cdot n + 1. \hspace{1cm} (36)$$
In particular, this shows that $u$ is smaller than $n$ if $\lambda > 1/i$. Finally, it can be verified that the inequalities given by (32) are valid for any two intervals $\Delta(L_1), \Delta(L_2) \in C_3(n, k, u, v)$.

4.1.3 Class $C^*(n, k)$

By the definition (14) of $l_0$, we have that

$$V_L \leq R^{-\lambda} (C_0 + 1) \max \{|A|, |B|\}.$$ 

This corresponds to the r.h.s. of (24) with $l = 1$ and thus the same arguments as in Sect. 4.1.1 can be utilized to show that (25) is satisfied. By substituting this into the definition of the height we obtain that

$$H(\Delta) \asymp |A|^{\frac{i+1}{2i}},$$

which in view of (23) implies that

$$|A| \asymp |B| \asymp \left(\frac{2^k}{R} \cdot R^n\right)^{\frac{2i}{i+1}}.$$  \hspace{1cm} (37)

A consequence of this estimate is that all intervals $\Delta(L) \in C^*(n, k)$ have comparable coefficients $A$ and $B$. In other words, if $\Delta(L_1), \Delta(L_2) \in C^*(n, k)$ then

$$|A_1| \asymp |B_1| \asymp |B_2| \asymp |A_2|.$$ 

To estimate the size of $V_L$ we make use of the fact that

$$V_L \leq (C_0 + 1) R^{-\lambda_{l_0+1}} \max \{|A|, |B|\} \leq (C_0 + 1) R^{-d} \max \{|A|, |B|\} \leq \left(\frac{2^k}{R} \cdot R^n\right)^{-\frac{i}{i+1}} \cdot \frac{\max \{|A|, |B|\}}{V_L \max \{|A|^{1/i}, |B|^{1/j}\}}.$$ 

This together with (12) and (37) enables us to verify that

$$V_L \leq \frac{|B|}{R \cdot H(\Delta)} \ll \left(\frac{2^k}{R} \cdot R^n\right)^{-\frac{j}{i+1}}.$$  \hspace{1cm} (38)
4.2 Additional subclasses $C(n, k, l, m)$ of $C(n, k, l)$

It is necessary to partition each class $C(n, k, l)$ of Type 1 intervals $\Delta(L)$ into the following subclasses to provide stronger control on $V_L$. For $m \in \mathbb{Z}$, let

$$C(n, k, l, m) := \{ \Delta(L(A, B, C)) \in C(n, k, l) \mid 2^{-m-1}R^{-\lambda l}(C_0+1) \max\{|A|, |B|\} < V_L \}.$$  \(39\)

In view of (24), it is easily verified that

$$0 \leq m \leq \lambda \log_2 R \asymp \log R.$$

An important consequence of introducing these subclasses is that for any two intervals $\Delta(L_1), \Delta(L_2)$ from $C(n, k, l, m)$ with $l \geq 1$ or from $C_1(n, k) \cap C(n, k, 0, m)$, we have that

$$V_{L_1} \asymp V_{L_2} \quad \text{and} \quad |A_1| \asymp |A_2|.$$  \(40\)

5 Defining the collection $\mathcal{J}_n$

We describe the procedure for constructing the collections $\mathcal{J}_n(n = 0, 1, 2, \ldots)$ that lie at the heart of the construction of the Cantor-type set $K_c(i, j) = K(J_0, R, r)$ of Sect. 3.2. Recall that each interval $J_n \in \mathcal{J}_n$ is to be nested in some interval $J_{n-1}$ in $\mathcal{J}_{n-1}$ and satisfy (21). We define $\mathcal{J}_0$ by induction on $n$.

For $n = 0$, we trivially have that (21) is satisfied for any interval $J_0 \subset I$. The point is that $H(\Delta) \geq 1$ and so there are no intervals $\Delta(L)$ satisfying the height condition $H(\Delta) < 1$. So take $\mathcal{J}_0 := \{ J_0 \}$. For the same reason (21) with $n = 1$ is trivially satisfied for any interval $J_1$ obtained by subdividing $J_0$ into $R$ closed intervals of equal length $c_1 R^{-1}$. Denote by $\mathcal{J}_1$ the resulting collection of intervals $J_1$.

In general, given $\mathcal{J}_n$ satisfying (21) we wish to construct a nested collection $\mathcal{J}_{n+1}$ of intervals $J_{n+1}$ for which (21) is satisfied with $n$ replaced by $n+1$. By definition, any interval $J_n$ in $\mathcal{J}_n$ avoids intervals $\Delta(L)$ arising from lines $L$ with height $H(\Delta)$ bounded above by $R^{n-1}$. Since any ‘new’ interval $J_{n+1}$ is to be nested in some $J_n$, it is enough to show that $J_{n+1}$ avoids intervals $\Delta(L)$ arising from lines $L$ with height $H(\Delta)$ satisfying (22); that is

$$R^{n-1} \leq H(\Delta) < R^n.$$

The collection of intervals $\Delta(L) \in \mathcal{R}$ satisfying this height condition is precisely the class $C(n) \cup C^*(n)$ introduced at the beginning of Sect. 4. In other words, it is the precisely the collection $C(n) \cup C^*(n)$ of intervals that come into play when attempting to construct $\mathcal{J}_{n+1}$ from $\mathcal{J}_n$. We now proceed with the construction.
Assume that \( n \geq 1 \). We subdivide each \( J_n \) in \( J_n \) into \( R \) closed intervals \( I_{n+1} \) of equal length \( c_1 R^{-(n+1)} \) and denote by \( I_{n+1} \) the collection of such intervals. Thus,

\[
|I_{n+1}| = c_1 R^{-(n+1)} \quad \text{and} \quad \# I_{n+1} = R \times \# J_n.
\]

It is obvious that the construction of \( I_{n+1} \) corresponds to the splitting procedure associated with the construction of a \( (I, R, r) \) Cantor set.

In view of the nested requirement, the collection \( J_{n+1} \) which we are attempting to construct will be a sub-collection of \( I_{n+1} \). In other words, the intervals \( I_{n+1} \) represent possible candidates for \( J_{n+1} \). The goal now is simple—it is to remove those ‘bad’ intervals \( I_{n+1} \) from \( I_{n+1} \) for which

\[
I_{n+1} \cap \Delta(L) \neq \emptyset \quad \text{for some} \quad \Delta(L) \in C(n) \cup C^*(n).
\]

The sought after collection \( J_{n+1} \) consists precisely of those intervals that survive. Formally, for \( n \geq 1 \) we let

\[
J_{n+1} := \{ I_{n+1} \in I_{n+1} : I_{n+1} \cap \Delta(L) = \emptyset \quad \text{for any} \quad \Delta(L) \in C(n) \cup C^*(n) \}.
\]

We claim that these collections of surviving intervals satisfy the following key statement. It implies that the act of removing ‘bad’ intervals from \( I_{n+1} \) is exactly in keeping with the removal procedure associated with the construction of a \( (J_0, R, r) \) Cantor set with \( R \) and \( r \) as described in Sect. 3.2.

**Proposition 1** Let \( \epsilon := (ij)^2/8 \) and with reference to Sect. 4 let

\[
C(n, l) := \bigcup_{k=0}^{\log_2 R} C(n, k, l), \quad C_1(n) := \bigcup_{k=0}^{\log_2 R} C_1(n, k),
\]

\[
C_2(n) := \bigcup_{k=0}^{\log_2 R} C_2(n, k) \quad \text{and} \quad \widetilde{C}_3(n, u) := \bigcup_{k=0}^{\log_2 R} \bigcup_{v=0}^{\lambda \log_2 R} C_3(n, k, u, v).
\]

Then, for \( R > R_0(\epsilon) \) large enough the following four statements are valid.

1. For any fixed interval \( J_{n-l} \in J_{n-l} \), the intervals from class \( C(n, l) \) with \( n/\lambda \geq l \geq 1 \) intersect no more than \( R^{1-\epsilon} \) intervals \( I_{n+1} \in I_{n+1} \) with \( I_{n+1} \subset J_{n-l} \).
2. For any \( n \geq 3n_0 \) where \( n_0 \) is defined by (16) and any fixed interval \( J_{n-n_0} \in J_{n-n_0} \), the intervals from class \( C^*(n) \) intersect no more than \( R^{1-\epsilon} \) intervals \( I_{n+1} \in I_{n+1} \) with \( I_{n+1} \subset J_{n-n_0} \).
3. For any fixed interval \( J_n \in J_n \), the intervals from class \( C_1(n) \) or \( C_2(n) \) intersect no more than \( R^{1-\epsilon} \) intervals \( I_{n+1} \in I_{n+1} \) with \( I_{n+1} \subset J_n \).
4. For any fixed interval \( J_{n-u} \in J_{n-u} \), the intervals from class \( \widetilde{C}_3(n, u) \) intersect no more than \( R^{1-\epsilon} \) intervals \( I_{n+1} \in I_{n+1} \) with \( I_{n+1} \subset J_{n-u} \).

**Remark 1** Note that in Part 1 we have that \( l < n/\lambda \) and in Part 2 we have that \( u \) is bounded above by (36). So in either part we have that \( l, u \leq n \) for all positive values \( n \). Therefore the collections \( J_{n-l} \) and \( J_{n-u} \) are well defined.
Remark 12 By definition, a planar curve $C := C_f$ is $C^{(2)}$ non-degenerate if $f \in C^{(2)}(I)$ and there exits at least one point $x \in I$ such that $f^{(n)}(x) \neq 0$. It will be apparent during the course of establishing Proposition 1 that the condition on the curvature is only required when considering Part 2. For the other parts only the two times continuously differentiable condition is required. Thus, Parts 1, 3 and 4 of the proposition remain valid even when the curve is a line. The upshot is that Proposition 1 remains valid for any $C^{(2)}$ curve for which $V_L$ is not too small and for such curves we are able to establish the analogue of Theorem 1. We will use this observation when proving Theorem 2.

5.1 Dealing with $\text{Bad}(0, 1) \cap C$

The construction of the collections $\mathcal{J}_n$ satisfying Proposition 1 requires that $i > 0$. However, by making use of the fact that $\text{Bad}(0, 1) \cap C = (\mathbb{R} \times \text{Bad}) \cap C$, the case $(i, j) = (0, 1)$ can be easily dealt with.

Let $R \geq 2$ be a large integer, and let

$$c_1 := \frac{2cR^2}{c_0} \quad \text{where} \quad 0 < c < \frac{1}{2R^2}.$$  \hspace{1cm} (42)

For a given rational number $p/q (q \geq 1)$, let $\Delta_C(p/q)$ be the “interval” on $C$ defined by

$$\Delta_C(p/q) := \left[ f^{-1}\left( \frac{p}{q} \pm \frac{c}{H(p/q)} \right) \right] \quad \text{where} \quad H(p/q) := q^2.$$  \hspace{1cm} (43)

In view of (6) the inverse function $f^{-1}$ is well defined. Next observe that the orthogonal projection of $\Delta_C(p/q)$ onto the $x$-axis is contained in the interval $\Delta(p/q)$ centered at the point $f^{-1}(p/q)$ with length

$$|\Delta(p/q)| := \frac{2c}{c_0H(p/q)}.$$  \hspace{1cm} (44)

By analogy with Sect. 2.1.1 the set $\text{Bad}_f(0, 1)$ can be described as the set of $x \in I$ such that $x \notin \Delta(p/q)$ for all rationals $p/q$. For the sake of consistency with the $i > 0$ situation, for $n \geq 0$ let

$$C(n) := \left\{ \Delta(p/q) : p/q \in \mathbb{Q} \text{ and } R^{n-1} \leq H(p/q) < R^n \right\}.$$  \hspace{1cm} (45)

Since $C(n) = \emptyset$ for $n = 0$, the following analogue of Proposition 1 allows us to deal with the $i = 0$ case. For $R \geq 4$ and any interval $J_n \in \mathcal{J}_n$, we have that

$$\#\{I_{n+1} \in \mathcal{I}_{n+1} : I_{n+1} \subset J_n \text{ and } \Delta(p/q) \cap I_{n+1} \neq \emptyset \text{ for some } \Delta(p/q) \in C(n)\} \leq 3.$$  \hspace{1cm} (46)
In short, it allows us to construct a \((J_0, \mathbf{R}, \mathbf{r})\) Cantor subset of \(\text{Bad}_f(0, 1)\) with

\[
\mathbf{R} := (R_n) = (R, R, R, \ldots)
\]

and

\[
\mathbf{r} := (r_{m,n}) = \begin{cases} 
3 & \text{if } m = n; \\
0 & \text{if } m < n.
\end{cases}
\]

To establish (43) we proceed as follows. First note that in view of (42), we have that

\[
\left| \Delta(p/q) \right| \leq 1.
\]

Thus, any single interval \(\Delta(p/q)\) removes at most three intervals \(I_{n+1}\) from \(\mathcal{I}_{n+1}\). Next, for any two rationals \(p_1/q_1, p_2/q_2 \in C(n)\) we have that

\[
\left| f^{-1}\left(\frac{p_1}{q_1}\right) - f^{-1}\left(\frac{p_2}{q_2}\right) \right| \geq \frac{1}{|f'(\xi)|q_1 q_2} \geq \frac{1}{c_0} R^{-n} > c_1 R^{-n} := |J_n|
\]

where \(\xi\) is some number between \(p_1/q_1\) and \(p_2/q_2\). Thus, there is at most one interval \(\Delta(p/q)\) that can possibly intersect any given interval \(J_n\) from \(\mathcal{J}_n\). This together with the previous fact establishes (43).

### 6 Forcing lines to intersect at one point

From this point onwards, all our effort is geared towards establishing Proposition 1. Fix a generic interval \(J \subset I\) of length \(c'_1 R^{-n}\). Note that the position of \(J\) is not specified and sometimes it may be more illuminating to picture \(J\) as an interval on \(C\). Consider all intervals \(\Delta(L)\) from the same class (either \(C(n, k, l, m), C^*(n, k), C_1(n, k) \cap C(n, k, 0, m), C_2(n, k)\) or \(C_3(n, k, u, v)\)) with \(\Delta(L) \cap J \neq \emptyset\). The overall aim of this section is to determine conditions on the size of \(c'_1\) so that the associated lines \(L\) necessarily intersect at single point.

#### 6.1 Preliminaries: estimates for \(F_L\) and \(F'_L\)

Let

\[
c'_1 \geq 2Kc^{1/2} \cdot 2^{-k} R.
\]

This condition guarantees that any interval \(\Delta(L) \in C(n, k, l, m)\) (or \(\Delta(L) \in C^*(n, k)\)) has length smaller than \(|J|\). Indeed,

\[
|\Delta(L)| = 2Kc^{1/2} \cdot (H(\Delta))^{-1} \leq 4Kc^{1/2} R \cdot 2^{-k} R^{-n} \leq |J|.
\]

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In this section we obtain various estimates for \( |F_L(x)| \) and \( |F'_L(x)| \) that are valid for any \( x \in J \). Recall, \( x_0 \) is as usual the point at which \( |F'_L(x)| \) attains its minimum with \( x \in \Delta(L) \).

**Lemma 2** Let \( 0 \leq m \leq \lambda \log_2 R, \ l \geq 0 \) and \( c'_1 \) be a positive parameter such that
\[
8C_0 c'_1 R^{-n} \leq 2^{-m} R^{-\lambda l}.
\] (45)

Let \( J \subset I \) be an interval of length \( c'_1 R^{-n} \). Let \( \Delta(L) \) be any interval from class \( C(n, k, l, m) \) such that \( \Delta(L) \cap J \neq \emptyset \). Then for any \( x \in J \) we have \( |F'_L(x)| \asymp V_L \) and
\[
|F_L(x)| \leq 5|J| V_L.
\] (46)

**Proof** A consequence of Taylor’s formula is that
\[
|F'_L(x) - V_L| = |A - B f'(x) - V_L| = |x - x_0| \cdot | - B f''(\tilde{x})| \leq (c'_1 + 2K c^{1/2} R) R^{-n} \cdot C_0 \max\{|A|, |B|\}
\]
(44)
\[
\leq 2c'_1 R^{-n} \cdot C_0 \max\{|A|, |B|\}
\]
(47)

where \( \tilde{x} \) is some point between \( x \) and \( x_0 \). Then by (44) and (45) together with the fact that \( \Delta(L) \in C(n, k, l, m) \) we get that
\[
|F'_L(x) - V_L| \leq \frac{1}{2} \cdot 2^{-m-1} R^{-\lambda l} \max\{|A|, |B|\} \leq \frac{1}{2} V_L.
\]

In other words, \( |F'_L(x)| \asymp V_L \). Then
\[
|F_L(x)| \leq |F_L(x_1)| + |x - x_1| \cdot |F'_L(\tilde{x})| \leq \frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\}} + 4|J| V_L
\]
where \( x_1 \) is the center of \( \Delta(L) \) and \( \tilde{x} \) is some point between \( x \) and \( x_1 \). However
\[
c \left( \max\{|A|^{1/i}, |B|^{1/j}\} \right)^{-1} = c^{1/2} V_L(H(\Delta))^{-1} \leq c^{1/2} R \cdot R^{-n} V_L \leq |J| V_L
\]
and as a consequence, (46) follows. \( \square \)

**Lemma 3** Assume \( c'_1 \) does not satisfy (45). Let \( J \subset I \) be an interval of length \( c'_1 R^{-n} \). Let \( \Delta(L(A, B, C)) \in C(n, k, l, m) \) such that \( \Delta(L) \cap J \neq \emptyset \). Then for any \( x \in J \) we have
\[
|F_L(x)| \leq 30C_0 |J|^2 \max\{|A|, |B|\}
\] (48)

and
\[
|F'_L(x)| \leq 10C_0 |J| \max\{|A|, |B|\}.
\] (49)
Proof In view of (47) it follows that
\[ |F'_L(x)| \leq 2c'_1 R^{-n} C_0 \max\{|A|, |B|\} + V_L. \]

By (39) we have that
\[ V_L \leq 2^{-m} R^{-\lambda L} \max\{|A|, |B|\} \leq 8C_0 |J| \max\{|A|, |B|\}. \]

Combining these estimates gives (49).

To establish inequality (48) we use Taylor’s formula. The latter implies the existence of some point \( \tilde{x} \) between \( x \) and \( x_1 \) such that
\[ |F_L(x)| \leq |F_L(x_1)| + |x - x_1||F'_L(x_1)| + \frac{1}{2} |x - x_1|^2 - B f''(\tilde{x}) | \leq 9C_0 |J|^2 \max\{|A|, |B|\} + 20C_0 |J|^2 \max\{|A|, |B|\}. \]

This together with the fact that the first of the three terms on the r.h.s. is bounded above by \( c_1^{1/2} V_L (H(\Delta))^{-1} \leq 8C_0 |J|^2 \max\{|A|, |B|\} \) yields (48).

The next lemma provides an estimate for \( F_L(x) \) and \( F'_L(x) \) in case \( \Delta(L) \) is of Type 2.

**Lemma 4** Let \( c'_1 \) be a positive parameter such that
\[ 1 \leq C_0 c'_1 \quad \text{and} \quad R^2 c \leq C_0 c'_1^2. \] (50)

Let \( J \subset I \) be an interval of length \( c'_1 R^{-n} \). Let \( \Delta(L) \) be any interval from class \( C^*(n, k) \) such that \( \Delta(L) \cap J \neq \emptyset \). Then for any \( x \in J \) we have
\[ |F_L(x)| \leq 9C_0 |J|^2 \max\{|A|, |B|\} \] (51)
and
\[ |F'_L(x)| \leq 3C_0 |J| \max\{|A|, |B|\}. \] (52)

Proof As in the previous two lemmas a simple consequence of Taylor’s formula is that there exists \( \tilde{x} \) between \( x \) and \( x_0 \) such that:
\[ |F'_L(x)| \leq V_L + |x - x_0| \cdot - B f''(\tilde{x}) | \leq R^{-n} \max\{|A|, |B|\} + 2C_0 |J| \max\{|A|, |B|\} \]
which by (50) leads to (52). For the first inequality, by Taylor’s formula we have that
\[ |F_L(x)| \leq \frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\}} + 8C_0 |J|^2 \max\{|A|, |B|\} \] (53)

On the other hand by (23) we have that
\[ H(\Delta) = (\max\{|A|^{1/i}, |B|^{1/j}\}|B|)^{1/2} \geq R^{n-1} \]
and so
\[
\frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\}} \leq \frac{R^2 c |B|}{R^{2n}} \leq C_0 |J|^2 \max\{|A|, |B|\}.
\]
This together with (53) yields (51). \(\square\)

6.2 Avoiding parallel lines

Consider all lines \(L_1, L_2, \ldots\) such that the corresponding intervals \(\Delta(L_1), \Delta(L_2), \ldots\) belong to the same class and intersect \(J\). Recall, \(|J| := c'_1 R^{-n}\). In this section, we determine conditions on \(c'_1\) which ensure that none of the lines \(L_i\) are parallel to one another.

Remark 13 For the sake of clarity and to minimize notation, throughout the rest of the paper we will often write \(V_1, V_2, \ldots\) instead of \(V_{L_1}, V_{L_2}, \ldots\) when there is no risk of ambiguity.

Lemma 5 Assume that there are at least two parallel lines \(L_1(A_1, B_1, C_1), L_2(A_2, B_2, C_2)\) such that \(\Delta(L_1) \cap J \neq \emptyset\) and \(\Delta(L_2) \cap J \neq \emptyset\). If \(\Delta(L_1), \Delta(L_2) \in C(n, k, l, m)\) and (45) is satisfied then
\[
c'_1 V_1 \min\{|A_1|, |B_1|\} \gg R^n. \tag{54}
\]
If \(\Delta(L_1), \Delta(L_2) \in C(n, k, l, m)\) and (45) is false or \(\Delta(L_1), \Delta(L_2) \in C^*(n, k)\) and (50) is true then
\[
c'_1 \sqrt{|A_1||B_1|} \gg R^n. \tag{55}
\]

Proof Assuming that \(L(A_1, B_1, C_1), L(A_2, B_2, C_2)\) are parallel implies that \(A_2 = tA_1, B_2 = tB_1, t \in \mathbb{Q}\). Without loss of generality, assume that \(|t| \leq 1\). This implies that \(|A_1| \geq |A_2|\) and \(|B_1| \geq |B_2|\). Then for an arbitrary point \(x \in J\), we have
\[
|tC_1 - C_2| = |tF_{L_1}(x) - F_{L_2}(x)|. \tag{56}
\]
The denominator of \(t\) divides both \(A_1\) and \(B_1\) so \(t\) is at most \(\min\{|A_1|, |B_1|\}\). Therefore the l.h.s. of (56) is at least \((\min\{|A_1|, |B_1|\})^{-1}\).

If \(c'_1\) satisfies (45) then the conditions of Lemma 2 are true. Therefore \(V_1 \nless V_2\) and r.h.s. of (56) is at most \(5|J|(V_1 + V_2) \ll c'_1 V_1 R^{-n}\). This together with the previous estimate for the l.h.s. of (56) gives (54). To establish the remaining part of the lemma, we exploit either Lemma 3 or Lemma 4 to show that
\[
\text{r.h.s. of (56)} \ll |J|^2 \max\{|A_1|, |B_1|\} = (c'_1 R^{-n})^2 \max\{|A_1|, |B_1|\}.
\]
This together with the previous estimate for the l.h.s. of (56) gives (55). \(\square\)
The upshot of Lemma 5 is that there are no parallel lines in the same class passing through a generic $J$ of length $c_1' R^{-n}$ if $c_1'$ is chosen to be sufficiently small so that (54) and (55) are violated; namely

$$0 < c_1' < \min \left\{ \frac{a R^n}{V_1 \min \{|A_1|, |B_1|\}}, \frac{b R^n}{\sqrt{|A_1||B_1|}} \right\}$$

where $a$ and $b$ are the implied positive constants associated with (54) and (55) respectively.

6.3 Ensuring lines intersect at one point

Recall, our aim is to determine conditions on $c_1'$ which ensure that all lines $L_j$ associated with intervals $\Delta_1(L)$ from the same class with $\Delta(L) \cap J \neq \emptyset$ intersect at one point. We will use the following well-known fact. For $i = 1, 2, 3$, let $L_i(A_i, B_i, C_i)$ be a line given by the equation $A_i x - B_i y + C_i = 0$. The lines do not intersect at a single point if and only if

$$\det \begin{pmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix} \neq 0.$$

Suppose there are at least three intervals $\Delta(L_1), \Delta(L_2), \Delta(L_3)$ from the same class (either $C(n, k, l)$, $C_1(n, k)$, $C_2(n, k)$, $C_3(n, k, u, v)$ or $C^*(n, k)$) that intersect $J$ but the corresponding lines $L_1, L_2$ and $L_3$ do not intersect at a single point. Then

$$\left| \det \begin{pmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix} \right| \geq 1.$$

Choose an arbitrary point $x \in J$. Firstly assume that the length $c_1' R^{-n}$ of $J$ satisfies (45) and that the intervals $\Delta(L_1), \Delta(L_2), \Delta(L_3)$ are of Type 1. Then Lemma 2 implies that

$$|F_{L_1}(x)| \ll |J| V_1.$$

The same inequalities are true for $F_{L_2}(x)$ and $F_{L_3}(x)$. We write this formally as

$$\left| \begin{pmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix} \cdot \begin{pmatrix} x \\ f(x) \\ 1 \end{pmatrix} \right| \ll \left( \begin{pmatrix} |J| V_1 \\ |J| V_2 \\ |J| V_3 \end{pmatrix} \right).$$

where $|(x_1, x_2, x_3)|$ denotes the vector $(|x_1|, |x_2|, |x_3|)$ and $(x_1, x_2, x_3) \ll (y_1, y_2, y_3)$ means that $x_1 \ll y_1$, $x_2 \ll y_2$ and $x_3 \ll y_3$. We shall make use of the following useful fact that is a consequence of the triangle inequality. If two vectors $x$ and $y$ from $\mathbb{R}^3$
satisfy $|x| \ll |y|$ then for any $3 \times 3$ real matrix $M$ we have $|Mx| \ll |M| \cdot |y|$ where the entries of $|M|$ are the absolute values of the correspondent entries in $M$. On applying this with

$$x = \begin{pmatrix} x \\ f(x) \\ 1 \end{pmatrix}, \quad y = \begin{pmatrix} |J| V_1 \\ |J| V_2 \\ |J| V_3 \end{pmatrix}, \quad M = \begin{pmatrix} A_1 B_1 C_1 \\ A_2 B_2 C_2 \\ A_3 B_3 C_3 \end{pmatrix}^{-1}$$

and by using Cramer’s rule we obtain the following inequality for the third row:

$$|J| (|V_1 (A_2 B_3 - A_3 B_2)| + |V_2 (A_1 B_3 - A_3 B_1)| + |V_3 (A_1 B_2 - A_2 B_1)|) \gg 1.$$  

Without loss of generality assume that the first term on the l.h.s. of this inequality is the largest of the three terms. Then

$$c'_1 |V_1 (A_2 B_3 - A_3 B_2)| \gg R^n. \quad (57)$$

In other words, if the lines $L_1, L_2$ and $L_3$ do not intersect at one point and $(45)$ is true for a given $c'_1$ then $(57)$ must also hold.

If $(45)$ is not true or the intervals $\Delta(L_1), \Delta(L_2), \Delta(L_3)$ are of Type 2 then we apply either Lemma 3 or Lemma 4. Together with Cramer’s rule, we obtain that

$$|J|^2 (\max(|A_1|, |B_1|)|A_2 B_3 - A_3 B_2| + \max(|A_2|, |B_2|)|A_1 B_3 - A_3 B_1| + \max(|A_3|, |B_3|)|A_1 B_2 - A_2 B_1|) \gg 1.$$  

Without loss of generality assume that the first of the three terms on the l.h.s. of this inequality is the largest. Then, we obtain that

$$c'_1 \sqrt{|\max(|A_1|, |B_1|)(A_2 B_3 - A_3 B_2)|} \gg R^n. \quad (58)$$

We now investigate the ramifications of the conditions $(57)$ and $(58)$ on specific classes of intervals.

6.3.1 Case $\Delta(L_1), \Delta(L_2), \Delta(L_3) \in C(n, k, l, m), l \geq 1$

We start by estimating the difference between $\frac{A_1}{B_1}$ and $\frac{A_2}{B_2}$. By $(24)$ we have that

$$\left| \frac{A_1}{B_1} - \frac{A_2}{B_2} \right| \leq \left| \frac{A_1}{B_1} - f'(x_{01}) \right| + |f'(x_{01}) - f'(x_{02})| + \left| f'(x_{02}) - \frac{A_2}{B_2} \right| \ll R^{-\lambda l} + |J| \quad (59)$$

where $x_{01}$ and $x_{02}$ are given by $V_1 := |A_1 - B_1 f'(x_{01})|$ and $V_2 := |A_2 - B_2 f'(x_{02})|$ respectively.

- Assume that $(45)$ is satisfied. This means that $|J| \ll R^{-\lambda l}$. We rewrite $(57)$ as

$$c'_1 |V_1 B_2 B_3| \left| \frac{A_2}{B_2} - \frac{A_3}{B_3} \right| \gg R^n.$$
Then in view of (26), (24) and (59) it follows that

\[
R^n \ll c'_1 R^{-\lambda l} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{n+\lambda(l+1)} \right)^{\frac{3i}{i+1}} R^{-\lambda l}.
\]

(45)

\[
\ll c'_1 R^{n-\frac{j-i}{i+1}n} R^{-\frac{2-j}{i+1} \lambda l} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{\lambda} \right)^{\frac{3i}{i+1}}.
\]

Since by assumption \( i \leq j \), the last inequality implies that if (57) holds then

\[
c'_1 \gg R^{l \frac{2-i}{i+1}} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{\lambda} \right)^{-\frac{3i}{i+1}}.
\]

Hence, the condition

\[
c'_1 \ll R^{l \frac{2-i}{i+1}} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{\lambda} \right)^{-\frac{3i}{i+1}}
\]

will contradict the previous inequality and imply that (57) is not satisfied. Note that similar arguments imply that if (54) holds then

\[
R^n \ll c'_1 R^{-\lambda l} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{n+\lambda(l+1)} \right)^{\frac{2i}{i+1}} = c'_1 R^{n-\frac{j-i}{i+1}n} R^{-\frac{j-i}{i+1} \lambda l} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{\lambda} \right)^{\frac{2i}{i+1}}.
\]

It follows that the condition

\[
c'_1 \ll R^{l \frac{j-i}{i+1}} \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{\lambda} \right)^{-\frac{3i}{i+1}}
\]

will contradict the previous inequality and imply that (54) is not satisfied.

The upshot is that for \( \lambda \) satisfying (11) the following condition on \( c'_1 \)

\[
c'_1 \leq \delta \cdot R^l \cdot \left( \frac{2^k c^{\frac{1}{2}}}{R} R^{\lambda} \right)^{-\frac{3i}{i+1}}
\]

will contradict both (57) and (54). Here \( \delta = \delta(i, j, c_0, C_0) > 0 \) is the absolute unspecified constant within the previous inequalities involving the Vinogradov symbols. In other words, if \( c'_1 \) satisfies (60), then the lines \( L_i \) associated with the intervals \( \Delta(L_i) \in C(n, k, l, m) \) with \( l \geq 1 \) such that \( \Delta(L_i) \cap J \neq \emptyset \) intersect at a single point.
• Assume that (45) is false. In this case $R^{-\lambda l} \ll R^\lambda |J|$. In view of (25) we have that $|A_1| \asymp |B_1|$ and inequality (58) implies that

$$c_1' \sqrt{|B_1B_2B_3|} \left| \frac{A_2}{B_2} - \frac{A_3}{B_3} \right| \gg R^n.$$  

In view of (26) and (59), it follows that to

$$R^n \ll (c_1')^2 R^{\lambda/2-n/2} \left( \frac{2^k c_1^2}{R} R^{n+\lambda(l+1)} \right)^{\frac{3i}{2(i+1)}}$$

which is equivalent to

$$R^n \ll c_1' R^{\lambda/3} \left( \frac{2^k c_1^2}{R} R^\lambda \right)^{-\frac{i}{i+1}} (R^{n+\lambda l})^{\frac{1}{i+1}}.$$  

This together with that fact that $i \leq 1/2$ and $\lambda l \leq n$ implies that

$$c_1' \gg R^{\frac{i}{i+1} \lambda l} \cdot \left( \frac{2^k c_1^2}{R} R^\lambda \right)^{-\frac{i}{i+1}} R^{-\frac{1}{2}}.$$  

By similar arguments, estimate (55) implies that

$$c_1' \gg R^{\frac{i}{i+1} \lambda l} \cdot \left( \frac{2^k c_1^2}{R} R^\lambda \right)^{-\frac{i}{i+1}}.$$  

The upshot is that for $\lambda$ satisfying (11), we obtain a contradiction to both these upper bound inequalities for $c_1'$ and thus to (58) and (55), if

$$c_1' \leq \delta \cdot R^l \cdot \left( \frac{2^k c_1^2}{R} R^\lambda \right)^{-\frac{i}{i+1}} R^{-\frac{1}{2}}. \quad (61)$$

In other words, if $c_1'$ satisfies (61) but not (45), then the lines $L_i$ associated with the intervals $\Delta(L_i) \in C(n, k, l, m)$ with $l \geq 1$ such that $\Delta(L_i) \cap J \neq \emptyset$ intersect at a single point.

6.3.2 Case $\Delta(L_1), \Delta(L_2), \Delta(L_3) \in C^*(n, k)$

For this class of intervals we will eventually make use of Lemma 4. With this in mind, we assume that (50) is valid. A consequence of (50) is that $R^{-n} \ll |J|$. It is readily
verified that in the case under consideration, the analogy to (59) is given by
\[ \left| \frac{A_1}{B_1} - \frac{A_2}{B_2} \right| \ll \frac{V_1}{B_1} + |J| + \frac{V_2}{B_2} \ll |J|. \]

Then by using (37), we find that inequality (58) implies that
\[ c_1' \gg R^{\frac{i}{i+1}} \cdot \left( \frac{2k}{R} \right)^{-\frac{2j}{i+1}}. \]

Similarly, inequality (55) implies the same upper bound for \( c_1' \). Thus if \( c_1' \) satisfies the condition
\[ c_1' \leq \delta \cdot R^{\frac{i}{i+1}} \cdot \left( \frac{2k}{R} \right)^{-\frac{2j}{i+1}}, \]
we obtain a contradiction to both (58) and (55).

6.3.3 Case \( \Delta(L_1), \Delta(L_2), \Delta(L_3) \in C_1(n, k) \cap C(n, k, 0, m) \)

In view of (27) and (29), inequality (57) implies that
\[ R^n \ll c_1' \left( \frac{2k}{R} \right)^{\frac{1}{i+1}} \left( \frac{2k c_1^2}{R} R^{n+\lambda} \right) \cdot \left( \frac{2k}{R} \right)^{\frac{2j}{i+1}}. \]

Hence, if \( c_1' \) satisfies the condition
\[ c_1' \leq \delta \cdot \left( \frac{2k c_1^2}{R} \right)^{-1}, \]
we obtain a contradiction to (57). Note that the same upper bound inequality for \( c_1' \) will also contradict (54).

For the class \( C_1(n, k) \) as well as all other subclasses of \( C(n, k, 0) \), when consider the intersection with a generic interval \( J \) of length \( c_1' R^{-n} \) the constant \( c_1' \) will always satisfy (45). Therefore, without loss of generality we assume that \( c_1' \) satisfies (45).

6.3.4 Case \( \Delta(L_1), \Delta(L_2), \Delta(L_3) \in C_2(n, k) \)

By (28), (30) and (31), inequality (57) implies that
\[ R^n \ll c_1' \left( \frac{2k}{R} \right)^{\frac{1}{i+1}} \left( \frac{2k c_1^2}{R} R^{n+\lambda} \right)^{\frac{j}{i+1} + \frac{2j}{i+1}} = c_1' \left( \frac{2k}{R} \right)^{\frac{1}{i+1}} \left( \frac{2k c_1^2}{R} R^{n+\lambda} \right). \]

It is now easily verified that if \( c_1' \) satisfies inequality (63) then we obtain a contradiction to (57).
6.3.5 Case $\Delta(L_1), \Delta(L_2), \Delta(L_3) \in C_3(n, k, u, v)$

By (34) and (35), inequality (57) implies that

$$R^n \ll c_1' \left( \frac{2k \zeta}{R} R^n \right)^{\frac{i}{j^2} + \frac{2i}{j^2}} \cdot R^{-\frac{2u+j+1}{j^2} \cdot \frac{\lambda_j}{j^2} \cdot R^{\lambda_j}} \ll c_1' \left( \frac{2k \zeta}{R} R^n \right) R^{\lambda_j - \lambda u j}.$$

Hence, if $c_1'$ satisfies the condition

$$c_1' \leq \delta \cdot \left( \frac{2k \zeta}{R} \right)^{-1} R^{\lambda u j - \lambda i},$$

we obtain a contradiction to (57). It is easily verified that if $c_1'$ satisfies this lower bound inequality, then we also obtain a contradiction to (54) as well.

It follows by (11) that $\lambda \geq 1/j$ and therefore the above lower bound inequality for $c_1'$ is true if

$$c_1' \leq \delta \cdot R^u \cdot R^{1-\lambda i} \cdot \frac{2k \zeta}{R}. \quad (64)$$

The upshot of this section is as follows. Assume that $\Delta(L_1), \Delta(L_2), \Delta(L_3)$ all intersect $J$ and belong to the same class. Then for each class, specific conditions for $c_1'$ have been determined that force the corresponding lines $L_1, L_2$ and $L_3$ to intersect at a single point. These conditions are (45), (50), (60), (61), (62), (63) and (64).

7 Geometrical properties of pairs $(A, B)$

Consider two intervals $\Delta(L_1), \Delta(L_2) \in \mathcal{R}$ where the associated lines $L_1(A_1, B_1, C_1)$ and $L_2(A_2, B_2, C_2)$ are not parallel. Denote by $P$ the point of intersection $L_1 \cap L_2$. To begin with we investigate the relationship between $P, \Delta(L_1)$ and $\Delta(L_2)$.

It is easily seen that

$$P = \left( \frac{p}{q}, \frac{r}{q} \right) = \left( \frac{C_2 B_1 - C_1 B_2}{A_1 B_2 - A_2 B_1}, \frac{A_1 C_2 - A_2 C_1}{A_1 B_2 - A_2 B_1} \right); \quad (p, r, q) = 1.$$ 

Therefore

$$A_1 B_2 - A_2 B_1 = tq, \quad C_1 B_2 - C_2 B_1 = -tp, \quad A_1 C_2 - A_2 C_1 = tr \quad (65)$$

for some integer $t$. Let $x_1$ and $x_2$ be two arbitrary points on $\Delta(L_1)$ and $\Delta(L_2)$. Since $P \in L_1 \cap L_2$, it follows that

$$A_1 \left( x_1 - \frac{p}{q} \right) - B_1 \left( f(x_1) - \frac{r}{q} \right) = F_{L_1}(x_1),$$
By Taylor’s formula the second equality can be written as

\[ A_2 \left( x_1 - \frac{p}{q} \right) - B_2 \left( f(x_1) - \frac{r}{q} \right) = F_{L_2}(x_2), \]

where \( \tilde{x} \) is some point between \( x_1 \) and \( x_2 \). This together with the first equality gives

\[ \left( A_1 - B_1 \right) \cdot \left( x_1 - \frac{p}{q} \right) = \left( F_{L_2}(x_2) + (x_1 - x_2)F'_{L_2}(\tilde{x}) \right). \]

which on applying Cramer’s rule leads to

\[ x_1 - \frac{p}{q} = \frac{B_1(F_{L_2}(x_2) + (x_1 - x_2)F'_{L_2}(\tilde{x})) - B_2 F_{L_1}(x_1)}{\det A}. \] (66)

and

\[ f(x_1) - \frac{r}{q} = \frac{A_1(F_{L_2}(x_2) + (x_1 - x_2)F'_{L_2}(\tilde{x})) - A_2 F_{L_1}(x_1)}{\det A}. \] (67)

Here

\[ \det A := -A_1 B_2 + A_2 B_1 \overset{(65)}{=} -tq. \]

Now assume that both intervals \( \Delta(L_1) \) and \( \Delta(L_2) \) belong to the same class and intersect a fixed generic interval \( J \) of length \( c_1' R^{-n} \). Then, we exploit the fact that \( x_1, x_2 \) can both be taken in \( J \). Firstly consider the case that \( J \) satisfies (45) and \( \Delta(L_1), \Delta(L_2) \) are of Type 1. Then by Lemma 2

\[ F_{L_2}(\tilde{x}) \asymp V_2, \quad F_{L_1}(x_1) \ll |J| V_1, \quad F_{L_2}(x_2) \ll |J| V_2 \quad \text{and} \quad |x_1 - x_2| \leq |J| = c_1' R^{-n}. \]

This together with (66) and (67) implies that

\[ \frac{|B_1| V_2 + |B_2| V_1}{R^n} \gg \frac{|q x_1 - p|}{c_1'}, \quad \frac{|A_1| V_2 + |A_2| V_1}{R^n} \gg \frac{|q f(x_1) - r|}{c_1'}. \] (68)

If \( J \) does not satisfy (45) and \( \Delta(L_1), \Delta(L_2) \) are of Type 1 we make use of Lemma 3 to estimate the size of \( F_{L_2}(x_2), F'_{L_2}(\tilde{x}) \) and \( F_{L_1}(x_1) \). This together with (66) and (67) implies that
We consider the situation when the point $P$ is close to $C$. More precisely, assume that there exists at least one point $(x, f(x)) \in C$ such that,

$$\left| x - \frac{p}{q} \right| < \frac{c}{2} \cdot q^{-1-i}, \quad \left| f(x) - \frac{r}{q} \right| < \frac{c}{2} \cdot q^{-1-j}.$$ 

We show that every such point $x$ is situated inside $\Delta(L_0)$ for some line $L_0$ passing through $P$. Indeed, each line $L(A, B, C)$ which passes through $P$ will satisfy the equation $Ap - Br + Cq = 0$. By Minkowski’s Theorem there exists an integer non-zero solution $A_0, B_0, C_0$ to this equation such that

$$|A_0| < q^i; \quad |B_0| < q^j.$$ 

Then

$$|F_{L_0}(x)| = |A_0x - B_0f(x) + C_0| = \left| A_0 \left( x - \frac{p}{q} \right) - B_0 \left( f(x) - \frac{r}{q} \right) \right| \leq cq^{-1}$$

since $|A_0 \cdot \frac{p}{q} - B_0 \cdot \frac{r}{q} + C_0| = 0$. In other words, the point $x \in \Delta(L_0)$.

7.2 The figure $F$

Consider all intervals $\Delta(L_i(A_i, B_i, C_i))$ from the same class (either $C(n, k, l, m)$ with $l \geq 1$, $C^*(n, k)$, $C_1(n, k) \cap C(n, k, 0, m)$, $C_2(n, k)$ or $C_3(n, k, u, v)$) which intersect a generic interval $J$ of length $c_1'R^{-n}$. In this section we investigate the implication of this on the coefficients of the corresponding lines $L_i$.

In Sect. 6 we have shown that under certain conditions on $c_1'$ all the corresponding lines $L_i$ intersect at one point. Assume now that the appropriate conditions are satisfied—this depends of course on the class of intervals under consideration. Let $P = (p/q, r/q)$ denote the point of intersection of the lines $L_i$. Then the triple $(A_i, B_i, C_i)$ will satisfy the equation

$$A_ip - B_ir + C_iq = 0 \quad A_i, B_i, C_i \in \mathbb{Z}.$$ 

Hence the points $(A_i, B_i) \in \mathbb{Z}^2$ lie in a lattice $L$ with fundamental domain of area equal to $q$. 

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Let $x_t$ be the point of minimum of $|F'_{L_t}(x)|$ on $\Delta(L_t)$. Define

$$\omega_x(P, J) := \max_t{|qx_t - p|} \quad \text{and} \quad \omega_y(P, J) := \max_t{|qf(x_t) - r|}.$$ 

Furthermore, let $t_1$ (resp. $t_2$) be the integer at which the maximum associated with $\omega_x$ (resp. $\omega_y$) is attained; i.e.

$$|qx_{t_1} - p| = \omega_x(P, J) \quad \text{and} \quad |qf(x_{t_2}) - r| = \omega_y(P, J).$$ 

We now consider several cases.

### 7.2.1 Interval $J$ satisfies (45) and intervals $\Delta(L_1)$ are of Type 1

Assume that the interval $J$ satisfies (45). Then on applying (68) with respect to the pair of intervals ($\Delta(L_t)$, $\Delta(L_{t_1})$) and ($\Delta(L_t)$, $\Delta(L_{t_2})$), we find that the following two conditions are satisfied:

$$\frac{|B_{t_1}V_t| + |B_{t_1}V_{t_1}|}{R^n} \geq v_x := \frac{\omega_x(P, J)}{c'_i c_x(C_0, c_0, i, j)} \quad t \neq t_1 \quad (70)$$

$$\frac{|A_{t_2}V_t| + |A_{t_2}V_{t_2}|}{R^n} \geq v_y := \frac{\omega_y(P, J)}{c'_i c_y(C_0, c_0, i, j)} \quad t \neq t_2, \quad (71)$$

where $c_x(C_0, c_0, i, j)$ and $c_y(C_0, c_0, i, j)$ are constants dependent only on $C_0, c_0, i$ and $j$.

Firstly consider inequality (70). Since all intervals $\Delta(L_t)$ lie in the same class $(C(n, k, l, m)$ with $l \geq 1, C_1(n, k) \cap C(n, k, 0, m), C_2(n, k)$ or $C_3(n, k, 0, v))$, then by either (32) or (40) we have $V_{t_1} \asymp V_t$. This together with (23) substituted into (70) gives

$$v_x \leq \frac{|B_{t_1}V_t| + |B_{t_1}V_{t_1}|}{R^n} \ll \frac{2^{k+1}}{R} \cdot \frac{(|B_{t_1}| + |B_t|) V_t}{H(A_t, B_t)}.$$ 

In other words,

$$v_x \ll \frac{2k c^\frac{1}{2}}{R} \cdot \frac{|B_t| + |B_{t_1}|}{\max\{|A_t|^{1/j}, |B_t|^{1/j}\}}. \quad (72)$$

This means that all pairs $(A_t, B_t)$ under consideration are situated within some figure defined by (72) which we denote by $F_x$. Note that $F_x$ depends on $B_{t_1}$ and $c'_i$ which in turn is defined by the point $P$, interval $J$ and the class of intervals $\Delta(L_t)$. The upshot is that all lines $L_t$ intersect at one point $P$ and all intervals $\Delta(L_t)$ intersect $J$ then all pairs $(A_t, B_t)$, except possibly one with $t = t_1$, lie in the set $F_x \cap L$.

When considering inequality (71), similar arguments enable us to conclude that all pairs $(A_t, B_t)$, except possibly one, lie in the set $F_y \cap L$ where $F_y$ is the figure defined by

$$v_y \ll \frac{2k c^\frac{1}{2}}{R} \cdot \frac{|A_t| + |A_{t_2}|}{\max\{|A_t|^{1/j}, |B_t|^{1/j}\}}. \quad (73)$$
This together with the previous statement for $F_x$ implies that all pairs $(A_t, B_t)$, except possibly two, lie in the set $F_x \cap F_y \cap L$.

### 7.2.2 Interval $J$ does not satisfy (45) and intervals $\Delta(L_t)$ are of Type 1

Now assume that interval $J$ does not satisfy (45). Then by applying (69) for the pair of intervals $(\Delta(L_t), \Delta(L_{t_1}))$ and $(\Delta(L_t), \Delta(L_{t_2}))$ we obtain the following two conditions:

\[
\frac{|B_{t_1}| \max(|A_t|, |B_t|) + |B_t| \max(|A_{t_1}|, |B_{t_1}|)}{R^{2n}} \geq \sigma_x := \frac{\omega_x(P, J)}{(c'_1)^2 c_x(C_0, i, j)} t \neq t_1
\]

\[
\frac{|A_{t_2}| \max(|A_t|, |B_t|) + |A_t| \max(|A_{t_2}|, |B_{t_2}|)}{R^{2n}} \geq \sigma_y := \frac{\omega_y(P, J)}{(c'_1)^2 c_y(C_0, i, j)} t \neq t_2
\]

which play the same role as (70) and (71) in the previous case. By similar arguments as before, we end up with two figures $F'_x$ and $F'_y$ defined as follows:

\[
\sigma_x \ll \frac{2^k c^{\frac{1}{2}}}{R^{n+1}} \cdot \frac{|B_t| + |B_{t_1}| \max(|A_t|, |B_t|, |A_{t_1}|, |B_{t_1}|)}{V_i \max(|A_t|^{1/i}, |B_t|^{1/j})}
\]  \hspace{1cm} (74)

and

\[
\sigma_y \ll \frac{2^k c^{\frac{1}{2}}}{R^{n+1}} \cdot \frac{|A_t| + |A_{t_1}| \max(|A_t|, |B_t|, |A_{t_2}|, |B_{t_2}|)}{V_i \max(|A_t|^{1/i}, |B_t|^{1/j})}
\]  \hspace{1cm} (75)

The upshot being that when $J$ does not satisfy (45) all pairs $(A_t, B_t)$, except possibly two, lie in the set $F'_x \cap F'_y \cap L$.

### 7.2.3 Intervals $\Delta(L_t)$ are of Type 2

As usual, for Type 2 intervals we assume that (50) is satisfied. With appropriate changes, such as the definition of $H(\Delta)$, the same arguments as above can be utilised to show that all pairs $(A_t, B_t)$, except possibly two, lie in the set $F^*_x \cap F^*_y \cap L$ where the figures $F^*_x$ and $F^*_y$ are defined as follows:

\[
\sigma_x \ll \frac{2^k}{R^2} \cdot \frac{|B_t|}{\max(|A_t|^{1/i}, |B_t|^{1/j})}
\]  \hspace{1cm} (76)

and

\[
\sigma_y \ll \frac{2^k}{R^2} \cdot \frac{|A_t|}{\max(|A_t|^{1/i}, |B_t|^{1/j})}
\]  \hspace{1cm} (77)

Indeed, the calculations are somewhat simplified since for intervals of Type 2 we have that $|A_t| \asymp |A_{t_1}| \asymp |A_{t_2}|$ and $|B_t| \asymp |B_{t_1}| \asymp |B_{t_2}|$. 
7.3 Restrictions to \( F_x \cap F_y \) in each class

We now use the specific properties of each class to reduce the size of \( F_x \cap F_y \) in each case.

- **Class** \( C(n, k, l, m) \) with \( l \geq 1 \) and interval \( J \) satisfies (45). Consider all intervals \( \Delta(L_t(A_t, B_t, C_t)) \) from \( C(n, k, l, m) \) such that the corresponding coordinates \((A_t, B_t)\) lie within the figure \( F_x \) defined by (72). First of all notice that by (25) we have \( |A_t| \approx |B_t| \). Then by (39) we obtain that

\[
\frac{|A_t|}{|V_t|} \asymp 2^m R^{\lambda l} \tag{78}
\]

which together with (40) and (72) implies that

\[
|B_t| \ll \left( \frac{2^k c x^1}{R v_x} \right)^{j/i}; \quad |A_t| \ll \left( \frac{2^k c x^1 B_t}{R v_x} \right)^i; \quad V_t \ll \frac{2^k c x^1}{R v_x} 2^{-m} R^{-\lambda l}.
\]

If we consider the coordinates \((A_t, B_t)\) within the figure \( F'_x \) defined by (73), we obtain the analogous inequalities:

\[
|A_t| \ll \left( \frac{2^k c x^1}{R v_x} \right)^{i/j}; \quad V_t \ll \left( \frac{2^k c x^1}{R v_y} \right)^j 2^{-m} R^{-\lambda l}.
\]

Hence, it follows that all coordinates \((A_t, B_t) \in F_x \cap F_y\) lie inside the box defined by

\[
|A_t| \ll \eta := \min \left\{ \frac{2^k c x^1}{R v_x}, \left( \frac{2^k c x^1}{R v_y} \right)^{j/i} \right\}; \quad |V_t| \ll |A_t| 2^{-m} R^{-\lambda l}. \tag{79}
\]

- **Class** \( C(n, k, l, m) \) with \( l \geq 1 \) and interval \( J \) does not satisfy (45). Consider all intervals \( \Delta(L_t(A_t, B_t, C_t)) \) from \( C(n, k, l, m) \) such that the corresponding coordinates \((A_t, B_t)\) lie inside \( F'_x \). As in previous case, (78) is valid which together with (40) and (74) implies that

\[
|A_t| \ll \left( \frac{2^k c x^1}{\sigma_x R^{n+1}} \cdot 2^m R^{\lambda l} |B_t| \right)^i \ll \frac{2^k c x^1}{\sigma_x R} \cdot 2^m R^{\lambda l-n}; \quad V_t \ll |A_t| 2^{-m} R^{-\lambda l}.
\]

If we consider the coordinates \((A_t, B_t)\) within the figure \( F'_y \) defined by (75), we obtain the analogous inequalities:

\[
|A_t| \ll \left( \frac{2^k c x^1}{\sigma_y R} \cdot 2^m R^{\lambda l-n} \right)^{i/j}; \quad V_t \ll |A_t| 2^{-m} R^{-\lambda l}.
\]
Denote by $\eta'$ the following minimum

$$
\eta' := \min \left\{ \frac{2^{k+m}c^2}{\sigma_x R}, \left( \frac{2^{k+m}c^2}{\sigma_y R} \right)^{i/j} \right\}.
$$

Then, since for intervals of Type 1 the parameter $l$ is always at most $l_0$ which in turn satisfies (14), it follows that all coordinates $(A_t, B_t) \in F'_x \cap F'_y$ lie inside the box defined by

$$
|A_t| \ll \eta'; \quad |V_t| \ll \eta'2^{-m}R^{-\lambda l}.
$$

- **Class $C^*(n, k)$.** Consider all intervals $\Delta(L_t(A_t, B_t, C_t))$ from $C^*(n, k)$ such that the corresponding coordinates $(A_t, B_t) \in F'_x \cap F'_y$. A consequence of that fact that we are considering Type 2 intervals is that $|B_t| \asymp |B_t|$. This together with (76) and (77) implies that

$$
|B_t| \ll \left( \frac{2^{2k}}{R^2\sigma_x} \right)^{j/i}; \quad |A_t| \ll \left( \frac{2^{2k}}{R^2\sigma_x} |B_t| \right)^i \ll \frac{2^{2k}}{R^2\sigma_x}; \quad |V_t| \ll |A_t|R^{-n}
$$

and

$$
|A_t| \ll \left( \frac{2^{2k}}{R^2\sigma_y} \right)^{i/j}.
$$

Denote by $\eta^*$ the following minimum

$$
\eta^* := \min \left\{ \frac{2^{2k}}{R^2\sigma_x}, \left( \frac{2^{2k}}{R^2\sigma_y} \right)^{i/j} \right\}.
$$

The upshot is that all coordinates $(A_t, B_t) \in F'_x \cap F'_y$ lie inside the box defined by

$$
|A_t| \ll \eta^*; \quad |V_t| \ll \eta^* \cdot R^{-n}.
$$

- **Class $C_1(n, k) \cap C(n, k, 0, m)$.** As mentioned in Sect. 6.3.3, for all subclasses of $C(n, k, 0)$, when consider the intersection with a generic interval $J$ of length $c'R^{-n}$ the constant $c'_1$ satisfies (45). In other words, $J$ always satisfies (45). With this in mind, consider all intervals $\Delta(L_t(A_t, B_t, C_t))$ from $C_1(n, k) \cap C(n, k, 0, m)$ such that the corresponding coordinates $(A_t, B_t)$ lie within the figure $F_x$ defined by (72). Then, the analogue of (78) is

$$
2^m |V_t| \asymp |A_t|.
$$

Although we cannot guarantee that $|B_t| \asymp |B_t|$, by (40) we have $V_t \asymp V_t$ and $|A_t| \asymp |A_t|$ which in turn implies that $\max\{|A_t|^{1/i}, |B_t|^{1/j}\} \asymp \max\{|A_t|^{1/i}, |B_t|^{1/j}\}$. So if $|B_t| \ll |B_t|$, it follows that
\[
\frac{|B_t| + |B_{t_1}|}{\max\{|A_t|^{1/j}, |B_t|^{1/j}\}} < \frac{|B_{t_1}|}{\max\{|A_{t_1}|^{1/j}, |B_{t_1}|^{1/j}\}}.
\]

This together with the previously displayed equation and (72) implies that
\[
|B_t| \leq |B_{t_1}| \ll \left(\frac{2^k c^\frac{1}{2}}{Rv_x}\right)^{j/i}.
\]

On the other hand, if \(|B_{t_1}| < |B_t|\) we straightforwardly obtain the same estimate for \(|B_t|\). So in both cases, we have that
\[
|B_t| \ll \left(\frac{2^k c^\frac{1}{2}}{Rv_x}\right)^{j/i}; \quad |A_t| \ll \left(\frac{2^k c^\frac{1}{2} \max\{|B_t|, |B_{t_1}|\}}{Rv_x}\right)^i \ll \frac{2^k c^\frac{1}{2}}{Rv_x} V_t \ll \frac{2^k c^\frac{1}{2}}{Rv_x} 2^{-m}.
\]

If we consider the coordinates \((A_t, B_t)\) within the figure \(F_y\), similar arguments together with inequality (73) yield the inequalities:
\[
|A_t| \ll \left(\frac{2^k c^\frac{1}{2}}{Rv_y}\right)^{j/l} \quad V_t \ll \left(\frac{2^k c^\frac{1}{2}}{Rv_y}\right)^l 2^{-m} R^{-\lambda l}.
\]

Notice that these inequalities are exactly the same as when considering ‘Class \(C(n, k, l, m)\) with \(l \geq 1\), interval \(J\) satisfies (45)’ above. The upshot is that all coordinates \((A_t, B_t) \in F_x \cap F_y\) lie inside the box defined by
\[
|A_t| \ll \eta; \quad |V_t| \ll 2^{-m}|A_t|.
\]  (82)

Here \(\eta\) is as in (79) and notice that (82) is indeed equal to (79) with \(l = 0\).

- **Class \(C_2(n, k)\).** In view of (32), for intervals \(\Delta(L_t(A_t, B_t, C_t))\) from \(C_2(n, k)\) we have that \(|B_t| \asymp |B_{t_1}|\). Moreover, although we cannot guarantee that \(|A_t| \asymp |A_{t_1}|\), we still have that \(\max\{|A_t|^{1/j}, |B_t|^{1/j}\} \asymp \max\{|A_{t_1}|^{1/j}, |B_{t_1}|^{1/j}\}\) and therefore one can apply the same arguments as when considering class \(C_1(n, k) \cap C(n, k, 0, m)\) above. As a consequence of (72) and (73), it follows that all coordinates \((A_t, B_t) \in F_x \cap F_y\) lie inside the box defined by
\[
|A_t| \ll \eta; \quad |B_t| \ll \eta^{j/i}.
\]  (83)

- **Class \(C_3(n, k, u, v)\).** Consider all intervals \(\Delta(L_t(A_t, B_t, C_t))\) from \(C_3(n, k, u, v)\) such that the corresponding coordinates \((A_t, B_t)\) lie within the figure \(F_x\). In view of (32), we have that \(|A_t| \asymp |B_t| \asymp |B_{t_1}| \asymp |A_{t_1}|\) and (33) implies that \(\max\{|A_t|^{1/i}, |B_t|^{1/i}\} > R^{\lambda u} |B_t|^{1/i}\). This together with (72) implies that
\[
\frac{Rv_x}{2^k c^\frac{1}{2}} \ll B_t^{-i/j} R^{-\lambda u} \Rightarrow B_t \ll \left(\frac{2^k c^\frac{1}{2}}{Rv_x}\right)^{j/i} R^{-\lambda u j/i}.
\]
and

$$|A_t| \ll \left( \frac{2^k c^\frac{1}{2}}{Ry_x} |B_t| \right)^i \ll \frac{2^k c^\frac{1}{2}}{Ry_x} \cdot R^{-\lambda ju}.$$  

If we consider the coordinates \((A_t, B_t)\) within the figure \(F_y\) defined by \((73)\), we obtain the analogous inequalities:

$$|A_t| \ll \left( \frac{2^k c^\frac{1}{2}}{Ry_y} \right)^{i/j}; \quad |B_t| \ll \frac{2^k c^\frac{1}{2}}{Ry_y} \cdot R^{-\lambda ju}.$$  

The upshot is that all coordinates \((A_t, B_t)\) from \(F_x \cap F_y\) lie inside the box defined by

$$|A_t| \ll \eta_3 := \min \left\{ \frac{2^k c^\frac{1}{2}}{Ry_x} \cdot R^{-\lambda ju}, \left( \frac{2^k c^\frac{1}{2}}{Ry_y} \right)^{i/j} \right\}$$

$$|B_t| \ll \eta_3^{i/j} \cdot R^{-\lambda ju} = \min \left\{ \left( \frac{2^k c^\frac{1}{2}}{Ry_x} \right)^{j/i} \cdot R^{-\frac{1}{2} \lambda ju}, \frac{2^k c^\frac{1}{2}}{Ry_y} \cdot R^{-\lambda ju} \right\}. \quad (84)$$

8 The finale

The aim of this section is to estimate the number of intervals \(\Delta(L_t)\) from a given class (either \(C(n, k, l, m)\), \(C^*(n, k)\), \(C_1(n, k) \cap C(n, k, 0, m)\), \(C_2(n, k)\) or \(C_3(n, k, u, v)\)) that intersect a fixed generic interval \(J\) of length \(c'_1 R^{-n}\). Roughly speaking, the idea is to show that one of the following two situations necessarily happens:

- All intervals \(\Delta(L_t)\) (except possibly at most two) intersect the thickening \(\Delta(L_0)\) of some line \(L_0\).
- There are not ‘too many’ intervals \(\Delta(L_t)\).

As in the previous section we assume that all the corresponding lines \(L_1, L_2, \ldots\) intersect at one point \(P = (p/q, r/q)\). Then the quantities \(\omega_x(P, J)\) and \(\omega_y(P, J)\) are well defined and the results from Sect. 6.3 are applicable.

8.1 Point \(P\) is close to \(C\)

Assume that

$$\omega_x(P, J) < \frac{c}{2} q^{-i} \quad \text{and} \quad \omega_y(P, J) < \frac{c}{2} q^{-j}. \quad (85)$$

Then, by the definition of \(\omega_x\) and \(\omega_y\), we have that for each \(\Delta(L_t)\)

$$\left| x_t - \frac{p}{q} \right| < \frac{c}{2} q^{-1-i} \quad \text{and} \quad \left| f(x_t) - \frac{r}{q} \right| < \frac{c}{2} q^{-1-j}.$$
As usual, \( x_t \) is the point in \( \triangle(L_t) \) at which \( |F'_t(x)| \) attains its minimum. In Sect. 7.1, it was shown that this implies that all points \( x_t \) lie inside \( \triangle(L_0) \) for some line \( L_0 \). It follows that all intervals \( \triangle(L_t) \) intersect \( \triangle(L_0) \).

• Assume that \( \triangle(L_0) \) has already been removed by the construction described in Sect. 5. In other words, \( \triangle(L_0) \in C(n_0, k_0) \) or \( \triangle(L_0) \in C^*(n_0, k_0) \) with \( (n_0, k_0) < (n, k) \). Recall that by \( (n_0, k_0) < (n, k) \) we mean either \( n_0 < n \) or \( n_0 = n \) and \( k_0 < k \). Then by the definition of the classes \( C(n, k) \) and \( C^*(n, k) \) each interval \( \triangle(L_t) \subset \triangle(L_0) \) can be ignored. Hence, the intervals \( \triangle(L_t) \) can in total remove at most two intervals of length

\[
\frac{R}{2^k} \cdot \frac{Kc^{\frac{1}{2}}}{R^n}
\]
on either side of \( \triangle(L_0) \).

• Otherwise, by (25) the length of \( \triangle(L_0) \) is bounded above by

\[
\frac{R}{2^k} \cdot \frac{2Kc^{\frac{1}{2}}}{R^n}.
\]

This implies that all the intervals \( \triangle(L_t) \) together do not remove more than a single interval \( \triangle^+(L_0) \) centered at the same point as \( \triangle(L_0) \) but of twice the length. Hence, the length of the removed interval is bounded above by

\[
\frac{R}{2^k} \cdot \frac{4Kc^{\frac{1}{2}}}{R^n}.
\]

The upshot is that in either case, the total length of the intervals removed by \( \triangle(L_t) \) is bounded above by (86).

8.2 Number of intervals \( \triangle(L_t) \) intersecting \( J \)

We investigate the case when at least one of the bounds in (85) for \( \omega_x \) or \( \omega_y \) is not valid. This implies the following for the quantities \( v_x \) and \( v_y \):

\[
v_x \geq \frac{cq^{-i}}{2c_1^{i}c_x(C_0, i, j)} \quad \text{or} \quad v_y \geq \frac{cq^{-j}}{2c_1^{i}c_y(C_0, i, j)}.
\]

The corresponding inequalities for \( \sigma_x \) \( \sigma_y \) are as follows:

\[
\sigma_x \geq \frac{cq^{-i}}{2(c_{1})^{2}c_x(C_0, i, j)} \quad \text{or} \quad \sigma_y \geq \frac{cq^{-j}}{2(c_{1})^{2}c_y(C_0, i, j)}.
\]

We now estimate the number of intervals \( \triangle(L_t) \) from the same class which intersect \( J \).
A consequence of Sect. 7.2 is that when considering intervals $\Delta(L_t(A_t, B_t, C_t)$ from the same class which intersect $J$, all except possibly at most two of the corresponding coordinates $(A_t, B_t)$ lie in the set $F_x \cap F_y \cap L$ or $F'_x \cap F'_y \cap L$, or $F^*_x \cap F^*_y \cap L$—depending on the class of intervals under consideration. Note that for two associated lines $L_1$ and $L_2$, the coordinates $(A_1, B_1)$, $(A_2, B_2)$ and $(0, 0)$ are not co-linear. To see this, suppose that the three points did lie on a line. Then $A_1/B_1 = A_2/B_2$ and so $L_1$ and $L_2$ are parallel. However, this is impossible since the lines $L_1$ and $L_2$ intersect at the rational point $P = (p/q, r/q)$.

Now let $M$ be the number of intervals $\Delta(L_t)$ from the same class intersecting $J$ and let $F$ denote the convex ‘box’ which covers $F \cap F_y$ or $F' \cap F'_y$ or $F^* \cap F^*_y$—depending on the class of intervals under consideration. In view of the discussion above, it then follows that the lattice points of interest in $F \cap L$ together with the lattice point $(0, 0)$ form the vertices of $(M - 1)$ disjoint triangles lying within $F$. Since the area of the fundamental domain of $L$ is equal to $q$, the area of each of these disjoint triangles is at least $q/2$ and therefore we have that

$$\frac{q}{2}(M - 1) \leq \text{area}(F).$$

(89)

We proceed to estimate $M$ for each class separately.

- **Classes** $C(n, k, l, m), l \geq 1$ and $C_1(n, k) \cap C(n, k, 0, m)$ and $J$ satisfies (45). By using either (79) for class $C(n, k, l, m), l \geq 1$ or (82) for class $C_1(n, k) \cap C(n, k, 0, m)$, it follows that

$$\text{area}(F) \ll \eta^2 2^{-m} R^{-\lambda l}$$

(87)

$$\leq \max \left\{ \left( \frac{2k c'_1}{R c^2} \right)^2, \left( \frac{2k c'_1}{R c^2} \right)^{2i/j} \right\} q^{2i} 2^{-m} R^{-\lambda l}.$$

This combined with (89) gives the following estimate

$$M \ll \max \{D^2, D^{2i/j}\} \cdot 2^{-m} R^{-\lambda l} \quad \text{where} \quad D := \frac{2k c'_1}{R c^2}.$$  

(90)

- **Class** $C(n, k, l, m), l \geq 1$ and $J$ does not satisfy (45). By (80), it follows that

$$\text{area}(F) \ll (\eta')^2 2^{-m} R^{-\lambda l}$$

(88)

$$\ll \max \left\{ \left( \frac{2k + m (c'_1)^2}{R c^2} \right)^2, \left( \frac{2k + m (c'_1)^2}{R c^2} \right)^{2i/j} \right\} q^{2i} \cdot 2^{-m} R^{-\lambda l}.$$

This combined with (89) gives the following estimate

$$M \ll \max \{D'^2, (D')^{2i/j}\} \cdot 2^m R^{-\lambda l} \quad \text{where} \quad D' := \frac{2k (c'_1)^2}{R c^2}.$$  

(91)
• **Class** $C^*(n, k)$. By (81), it follows that

$$\text{area}(F) \ll (\eta^*)^2 R^{-n} \ll \max \left\{ \left( \frac{2^k c'_1}{Rc_1^2} \right)^4, \left( \frac{2^k c'_1}{Rc_1^2} \right)^{4/i/j} \right\} q^{2i} R^{-n}. $$

This combined with (89) gives the following estimate

$$M \ll \max \{ (D^*)^4, (D^*)^{4i/j} \} \cdot R^{-n} \quad \text{where} \quad D^* := \frac{2^k c'_1}{Rc_1^{1/2}}. \quad (92)$$

• **Class** $C_2(n, k)$. By (83), it follows that

$$\text{area}(F) \ll \eta^{1+i/j} \ll \max \{ D^{1/i}, D^{1/j} \} q. $$

This combined with (89) gives the following estimate

$$M \ll \max \{ D^{1/i}, D^{1/j} \}. \quad (93)$$

• **Class** $C_3(n, k, u, v)$. By (84), it follows that

$$\text{area}(F) \ll \eta_3^{1/i} R^{-\lambda uj} \ll \max \left\{ (D \cdot R^{-\lambda uj} q^i)^{1/i}, (D \cdot q^i)^{1/j} \right\} R^{-\lambda uj} \ll \max \{ D^{1/i} R^{-\lambda uj(i+i)/i}, D^{1/j} R^{-\lambda uj} \} \cdot q.$$  

This combined with (89) gives the following estimate

$$M \ll \max \{ D^{1/i} R^{-\lambda uj(i+i)/i}, D^{1/j} R^{-\lambda uj} \}. \quad (94)$$

8.3 Number of subintervals removed by a single interval $\Delta(L)$

Let $c_1 := c^{1/2} R^{1+\omega}$ and $\omega := ij/4$ be as in (12). Consider the nested intervals $J_n \subset J_{n-1} \subset J_{n-2} \subset \cdots \subset J_0$ where $J_k \in \mathcal{J}_k$ with $0 \leq k \leq n$. Consider an interval $\Delta(L) \in C(n) \cap C^*(n)$ such that $\Delta(L) \cap J_n \neq \emptyset$. We now estimate the number of intervals $I_{n+1} \in \mathcal{I}_{n+1}$ such that $\Delta(L) \cap I_{n+1} \neq \emptyset$ with $I_{n+1} \subset J_n$. With reference to the construction of $\mathcal{J}_{n+1}$, the desired estimate is exactly the same as the number of intervals $I_{n+1} \in \mathcal{I}_{n+1}$ which are removed by the interval $\Delta(L)$. By definition, the length of any interval $I_{n+1}$ is $c_1 R^{-n-1}$ and the length of $\Delta(L)$ is $2K c^{1/2} (H(\Delta))^{-1}$. Thus, the number of removed intervals is bounded above by

$$\frac{2 K c^{1/2} R^{n+1}}{c_1 H(\Delta)} + 2 = \frac{2 K R^{n-\omega}}{H(\Delta)} + 2. \quad (95)$$

Since $R^{n-1} \ll H(\Delta) < R^n$, the above quantity varies between 2 and $[2 K R^{1-\omega}] + 2$. 

\[ \circ \] Springer
8.4 Condition on \( l \) so that \( J_{n-l} \) satisfies (45)

Consider an interval \( J_{n-l} \). Recall, by definition

\[
|J_{n-l}| = c_1 R^{-n+l} = (c_1 R^l) \cdot R^{-n}.
\]

So in this case the parameter \( c'_1 \) associated with the generic interval \( J \) is equal to \( c_1 R^l \) and by the choice of \( c_1 \) it clearly satisfies (44). We now obtain a condition on \( l \) so that (45) is valid when considering the intersection of intervals from \( C(n, k, l, m) \) with \( J_{n-l} \). With this in mind, on using the fact that \( m \leq \lambda \log_2 R \), it follows that

\[
8C_0 \cdot c_1 R^{-n+l} \leq R^{-\lambda(l+1)} \leq 2^{-m} R^{-\lambda l}.
\]

Thus, (45) is satisfied if

\[
8C_0 \cdot c_1 R^\lambda \cdot R^{l(\lambda+1)} \leq R^n.
\]

By the choice of \( c_1 \) and in view of (12), we have that for \( R \) sufficiently large

\[
c_1 < \frac{1}{8C_0 R^\lambda}.
\]

(96)

Therefore, (45) is satisfied for \( J_{n-l} \) if

\[
l \leq \frac{n}{\lambda + 1}.
\]

Notice that this is always the case when \( l = 0 \).

8.5 Proof of Proposition 1

Define the parameters \( \epsilon := \frac{1}{2} (ij) \omega = \frac{1}{8} (ij)^2 \) and

\[
\tilde{c}(k) := \begin{cases} \frac{c_1 R^{e-\omega}}{2^k} & \text{if } 2^k < R^{1-\omega} \\ \frac{c_1 R^{e-1}}{c_1 \tilde{c}} & \text{if } 2^k \geq R^{1-\omega}. \end{cases}
\]

(97)

Consider an interval \( J_{n-l} \in J_{n-l} \). Cover \( J_{n-l} \) by intervals \( J_{l,1}, \ldots, J_{l,d} \) of length \( \tilde{c}(k) R^{-n+l} \). Note that by the choice of \( c_1 \) and \( R \) sufficiently large the quantity \( c'_1 = \tilde{c}(k) R^l \) satisfies (44). It is easily seen that the number \( d \) of such intervals is estimated as follows:

\[
\begin{cases} d \leq 2^k R^{\omega-\epsilon} & \text{if } 2^k < R^{1-\omega} \\ d \leq R^{1-\epsilon} & \text{if } 2^k \geq R^{1-\omega}. \end{cases}
\]

(98)
8.5.1 Part 1 of Proposition 1

A consequence of Sect. 6.3 is that if \( c'_1 = c_1 R^l \) satisfies either (60) or (61), depending on whether inequality (45) holds or not, then all lines \( L \) associated with intervals \( \Delta(L) \in C(n, k, l, m) \) such that \( \Delta(L) \cap J_{n-1} \neq \emptyset \) intersect at a single point. This statement remains valid if the interval \( J_{n-1} \) is replaced by any nested interval \( J_l, t \).

Inequality (60) is equivalent to

\[
c_1 \leq \delta \left( \frac{2k c_2^2}{R} R^\lambda \right)^{-\frac{3i}{i+1}} \quad \text{or} \quad c_1^\frac{1}{2} \leq \delta \left( \frac{2k c_2^2}{R} R^\lambda \right)^{-\frac{3i}{i+1}} R^{-1-\omega}
\]

and inequality (61) is equivalent to

\[
c_1 \leq \delta \left( \frac{2k c_2^2}{R} R^\lambda \right)^{-\frac{i}{i+1}} R^{-\lambda/3} \quad \text{or} \quad c_1^\frac{1}{2} \leq \delta \left( \frac{2k c_2^2}{R} R^\lambda \right)^{-\frac{i}{i+1}} R^{-1-\omega-\lambda/3}.
\]

In view of (12), for \( R \) large enough both of these upper bound inequalities on \( c \) are satisfied. Thus the coordinates \( (A, B) \) associated with intervals \( \Delta(L) \in C(n, k, l, m) \) intersecting \( J_{l, t} \) where \( 1 \leq t \leq d \), except possibly at most two, lie within the figure \( F := F_x \cap F_y \cap L \) or \( F := F'_x \cap F'_y \cap L \)—depending on whether or not \( J_{l, t} \) satisfies (45). Moreover, note that the figure \( F \) is the same for \( 1 \leq t \leq d \); i.e. it is independent of \( t \).

If (85) is valid, then all intervals \( \Delta(L) \) that intersect \( J_{l, t} \) can remove at most two intervals of total length bounded above by

\[
R \frac{4Kc}{2^k} \cdot \frac{c_2}{R^n}.
\]

Then, it follows that the number of removed intervals \( I_{n+1} \subset J_{n-1} \) is bounded above by

\[
\left( R \frac{4Kc}{2^k} \cdot \frac{c_2}{R^n} \cdot \frac{1}{|I_{n+1}|} + 4 \right) \cdot d = 4 \left( \frac{K R^{1-\omega}}{2^k} + 1 \right) \cdot d \ll \left( \frac{R^{1-\omega}}{2^k} + 1 \right) \cdot d \ll R^{1-\epsilon}.
\]

(99)

Otherwise, if (85) is false then the number \( M \) of intervals \( \Delta(L) \subset C(n, k, l, m) \) that intersect some \( J_{l, t} \) \( (1 \leq t \leq d) \) can be estimated by (90) if \( J_{l, t} \) satisfies (45) and by (91) if (45) is not satisfied. This leads to the following estimates.

- **\( M \) is bounded by (90)** and \( 2^k < R^{1-\omega} \). Then

\[
M \ll \left( \frac{2k c_2^\frac{1}{2} R^{1+\epsilon} R^l}{2^k R c_2^\frac{1}{2}} \right)^2 2^{-m} R^{-\lambda l} \leq (R^\epsilon)^2 \cdot R^{2(\lambda l)}.
\]

By (11), \( \lambda > 2 \) and therefore

\[
M \ll R^{2\epsilon}.
\]
• $M$ is bounded by (90) and $2^k \geq R^{1-\omega}$. Then

$$M \ll \left(\frac{2^k c^2 R^{\omega+\epsilon} R^l}{R c^2}\right)^2 2^{-m} R^{-\lambda l} \leq (R^{\omega+\epsilon})^2.$$ 

because $R \geq 2^k$ and $\lambda > 2$.

• $M$ is bounded by (91) and $2^k < R^{1-\omega}$. Then

$$M \ll \left(\frac{2^k c R^{2+\epsilon} R^{2l}}{R c^2}\right)^2 2^m R^{-\lambda l} \leq c \cdot \frac{2^m R^2}{2^{2k}} R^{4\epsilon} \cdot R^{(4-\lambda)l}.$$ 

Since $\lambda > 4$ by (11) and $c < R^{-2-\lambda}$ by (12), it follows that $M \ll R^{4\epsilon}$.

• $M$ is bounded by (91) and $2^k \geq R^{1-\omega}$. Then

$$M \ll \left(\frac{2^k c R^{2\epsilon+2\omega} R^{2l}}{R c^2}\right)^2 2^m R^{-\lambda l} \leq c \cdot \frac{2^m R^{4(\epsilon+\omega)}}{2^{2k}} \cdot R^{(4-\lambda)l}.$$ 

Again, by the choice of $\lambda$ and $c$ it follows that $M \ll R^{4(\epsilon+\omega)}$.

The upshot of the above upper bounds on $M$ is that

$$M \ll \begin{cases} (R^{\epsilon})^4 & \text{if } 2^k < R^{1-\omega} \\ (R^{\omega+\epsilon})^4 & \text{if } 2^k \geq R^{1-\omega}. \end{cases} \quad (100)$$

In addition to these $M$ intervals, we can have at most another $2d$ intervals—two for each $1 \leq t \leq d$ corresponding to the fact that there may be up to two exceptional intervals $\Delta(L(A, B, C))$ with associated coordinates $(A, B)$ lying outside the figure $F$. By analogy with (99), these intervals remove at most $R^{1-\epsilon}$ intervals $I_{n+1} \in I_{n+1}$ with $I_{n+1} \subset J_{n-1}$.

On multiplying $M$ by the number of intervals $I_{n+1} \in I_{n+1}$ removed by each $\Delta(L)$ from $C(n, k, l, m)$, we obtain via (95) that the total number of intervals $I_{n+1} \in I_{n+1}$ with $I_{n+1} \subset J_{n-1}$ removed by $\Delta(L) \in C(n, k, l, m)$ is bounded above by

$$2 R^{1-\epsilon} + \left(\frac{2 K R^{n-\omega}}{H(\Delta)} + 2\right) \cdot (R^{\epsilon})^4 \ll R^{1-\epsilon} + \left(\frac{R^{1-\omega}}{2^k} + 1\right) \cdot (R^{\epsilon})^4$$

$$\ll R^{1-\epsilon} + R^{1-\omega + 4\epsilon} \quad \text{if } 2^k < R^{1-\omega}$$

and by

$$2 R^{1-\epsilon} + \left(\frac{2 K R^{n-\omega}}{H(\Delta)} + 2\right) \cdot (R^{\omega+\epsilon})^4 \ll R^{1-\epsilon} + \left(\frac{R^{1-\omega}}{2^k} + 1\right) \cdot (R^{\omega+\epsilon})^4$$

$$\ll R^{1-\epsilon} + R^{4(\omega+\epsilon)} \quad \text{if } 2^k \geq R^{1-\omega}.$$
Since $\omega = \frac{1}{4}ij$ and $\epsilon = \frac{1}{2}(ij)\omega$, in either case the number of removed intervals $I_{n+1}$ is $\ll R^{1-\epsilon}$. Now recall that the parameters $k$ and $m$ can only take on a constant times log $R$ values. Hence, it follows that

$$\# \{I_{n+1} \in \mathcal{I}_{n+1} : I_{n+1} \subset J_{n-1}, \exists \Delta(L) \in C(n, l), \Delta(L) \cap I_{n+1} \neq \emptyset\} \ll \log^2 R \cdot R^{1-\epsilon}.$$ 

For $R$ large enough the r.h.s. is bounded above by $R^{1-\epsilon/2}$.

### 8.5.2 Part 2 of Proposition 1

Consider an interval $J_{n-n_0} \subset J_{n-n_0}$, where $n_0$ is defined by (16) and $n \geq 3n_0$. Cover $J_{n-n_0}$ by intervals $J_{n_0,1}, \ldots, J_{n_0,d}$ of length $\tilde{c}(k)R^{-n+n_0}$ where $\tilde{c}(k)$ is defined by (97). Notice that $d$ satisfies (98). Also, in view of (16) it follows that $c'_1 := \tilde{c}(k)R$ satisfies (50). Therefore, Lemma 4 is applicable to the intervals $J_{n_0,t}$ with $1 \leq t \leq d$ and indeed is applicable to the whole interval $J_{n-n_0}$.

To ensure that all lines associated with $\Delta(L) \subset C^*(n, k)$ such that $\Delta(L) \cap J_{n-n_0} \neq \emptyset$ intersect at one point, we need to guarantee that (62) is satisfied for $c'_1 := c_1 R^{n_0}$. This is indeed the case if

$$c_1 R^{n_0} \leq \delta \cdot R^{\frac{i}{1+i}} \left(\frac{2^k}{R}\right)^{-\frac{2}{i+1}}, \quad (101)$$

Since $i \leq j$ we have that $\frac{j}{1+i} = \frac{1}{3}$ which together with the fact that $n \geq 3n_0$ implies that (101) is true if

$$c_1^\frac{1}{i} \leq \delta \cdot \left(\frac{2^k}{R}\right)^{-\frac{2}{i+1}} R^{-1-\omega}.$$ 

In view of (12), for $R$ large enough this upper bound inequality on $c$ is satisfied. Thus the coordinates $(A, B)$ of all except possibly at most two lines $L(A, B, C)$ associated with intervals $\Delta(L(A, B, C)) \subset C^*(n, k)$ with $\Delta(L) \cap J_{n_0,t} \neq \emptyset$ lie within the figure $F := F_x^* \cap F_y^* \cap L$. By analogy with Part 1, if (85) is valid then the number of intervals $I_{n+1} \subset J_{n-n_0}$ removed by intervals $\Delta(L)$ is bounded above by $R^{1-\epsilon}$. Otherwise, the number $M$ of intervals $\Delta(L) \subset C^*(n, k)$ that intersect some $J_{n_0,t}$ ($1 \leq t \leq d$) with associated coordinates $(A, B) \subset F$ can be estimated by (92). Thus

$$M \ll \left(\frac{2^k \tilde{c}(k)}{Rc_1^2}\right)^4 R^{-n} \begin{cases} (R^\epsilon)^4 R^{-n} & \text{if } 2^k < R^{1-\omega} \\ (R^\epsilon+\omega)^4 R^{-n} & \text{if } 2^k \geq R^{1-\omega}. \end{cases}$$

Since $n \geq 1$ and $\omega + \epsilon < 1/4$, it follows that $M \ll 1$. Now the same arguments as in Part 1 above can be utilized to verify that

$$\# \{I_{n+1} \in \mathcal{I}_{n+1} : I_{n+1} \subset J_{n-1}, \exists \Delta(L) \in C^*(n), \Delta(L) \cap I_{n+1} \neq \emptyset\} \ll \log R \cdot R^{1-\epsilon}.$$ 

For $R$ large enough the r.h.s. is bounded above by $R^{1-\epsilon/2}$.
8.5.3 Part 3 of Proposition 1

Consider an interval \( J_n \in \mathcal{J}_n \). Cover \( J_n \) by intervals \( J_{0,1}, \ldots, J_{0,d} \) of length \( \tilde{c}(k)R^{-n} \) where \( \tilde{c}(k) \) is defined by (97). As before, \( d \) satisfies (98).

First we consider intervals \( \Delta(L) \) from class \( C_1(n, k) \cap C(n, k, 0, m) \) such that \( \Delta(L) \cap J_n \neq \emptyset \). In this case, the conditions (82) on the convex ‘box’ containing the figure \( F_x \cap F_y \cap L \) and the conditions (90) on \( M \) are the same as those when dealing with the class \( C(n, k, l, m) \) in Part 1 above. Thus, analogous arguments imply that

\[
\# \{ I_{n+1} \in \mathcal{I}_{n+1} : I_{n+1} \subset J_n, \exists \Delta(L) \in C_1(n), \Delta(L) \cap I_{n+1} \neq \emptyset \} \ll R^{1-\epsilon/2}.
\]

Next we consider intervals \( \Delta(L) \) from class \( C_2(n, k) \) such that \( \Delta(L) \cap J_n \neq \emptyset \). A consequence of Sect. 6.3 is that if \( c_1' := c_1 \) satisfies (63), then all lines \( L \) associated with intervals \( \Delta(L) \in C_2(n, k) \) such that \( \Delta(L) \cap J_n \neq \emptyset \) intersect at a single point. Inequality (63) is equivalent to

\[
c_1 \leq \delta \cdot \left( \frac{2k^2 \tilde{c}(k)}{R^k} \right)^{-1} \quad \text{or} \quad c_1^2 \leq \delta \cdot \left( \frac{2k^2 \tilde{c}(k)}{R^k} \right)^{-1} R^{-1-\omega}.
\]

In view of (12), for \( R \) large enough this upper bound inequality on \( c \) is satisfied. Thus the coordinates \( (A, B) \) associated with intervals \( \Delta(L(A, B, C)) \in C_2(n, k) \) intersecting \( J_{0,t} \) where \( 1 \leq t \leq d \), except possibly at most two, lie within the figure \( F := F_x \cap F_y \cap L \). We now follow the arguments from Part 1. If (85) is valid, then we deduce that the total number of intervals \( I_{n+1} \subset J_n \) removed by intervals \( \Delta(L) \) is bounded above by (99). Otherwise, the number \( M \) of intervals \( \Delta(L) \in C_2(n, k) \) that intersect some \( J_{0,t} \) \( (1 \leq t \leq d) \) with associated coordinates \( (A, B) \in F \) can be estimated by (93). Thus, with \( c_1' := \tilde{c}(k) \) given by (97) we obtain that

\[
M \ll \left( \frac{2k^2 \tilde{c}(k)}{Rc^2} \right)^{1/i} \leq \begin{cases} \left( R^\epsilon \right)^{1/i} & \text{if } 2k < R^{1-\omega} \\ \left( R^{\omega+\epsilon} \right)^{1/i} & \text{if } 2k \geq R^{1-\omega}. \end{cases}
\]

It follows via (95) that the total number of intervals \( I_{n+1} \in \mathcal{I}_{n+1} \) with \( I_{n+1} \subset J_n \) removed by \( \Delta(L) \in C_2(n, k) \) is bounded above by

\[
2R^{1-\epsilon} + \left( \frac{2R^{n-\omega}}{H(\Delta)} + 2 \right) \cdot \left( R^\epsilon \right)^{1/i} \leq \begin{cases} R^{1-\epsilon} + \left( \frac{R^{1-\omega}}{2} + 1 \right) \cdot \left( R^\epsilon \right)^{1/i} & \text{if } 2k < R^{1-\omega} \\ R^{1-\epsilon} + R^{(\omega+\epsilon)/i} & \text{if } 2k \geq R^{1-\omega}. \end{cases}
\]

and

\[
2R^{1-\epsilon} + \left( \frac{2R^{n-\omega}}{H(\Delta)} + 2 \right) \cdot \left( R^{\omega+\epsilon} \right)^{1/i} \leq \begin{cases} R^{1-\epsilon} + \left( \frac{R^{1-\omega}}{2} + 1 \right) \cdot \left( R^{\omega+\epsilon} \right)^{1/i} & \text{if } 2k < R^{1-\omega} \\ R^{1-\epsilon} + R^{(\omega+\epsilon)/i} & \text{if } 2k \geq R^{1-\omega}. \end{cases}
\]
Since $\omega = \frac{1}{4} i j$ and $\epsilon = \frac{1}{7} (ij) \omega$, in either case the number of removed intervals $I_{n+1}$ is $\ll R^{1-\epsilon}$. Hence, we obtain that

$$\# \{ I_{n+1} \in I_{n+1} : I_{n+1} \subset J_n, \exists \Delta(L) \in C_2(n), \Delta(L) \cap I_{n+1} \neq \emptyset \} \ll \log R \cdot R^{1-\epsilon}.$$ 

For $R$ large enough the r.h.s. is bounded above by $R^{1-\epsilon/2}$.

### 8.5.4 Part 4 of Proposition 1

The proof is pretty much the same as for Parts 1-3. Consider an interval $J_{n-u} \in J_{n-u}$. Cover $J_{n-u}$ by intervals $J_{n-u}, J_{n-d}$ of length $c(k) R^{-n+u}$ where $c(k)$ is given by (97). As usual, $d$ satisfies (98). Recall, that $C_3(n, k, u, v) \subset C(n, k, 0)$ and for all subclasses of $C(n, k, 0)$ when consider the intersection with a generic interval $J$ of length $c_1 R^{-n}$ we require the constant $c_1'$ to satisfy (45)—see Sect. 6.3.3. Thus, to begin with we check that the interval $J_{n-u}$ satisfies (45). Now, with $c_1' := c_1 R^u$ and $l = 0$, together with the fact that $m \leq \lambda \log_2 R$, the desired inequality (45) would hold if

$$8 C_0 c_1 R^{u-n} \leq R^{-\lambda}.$$ 

It is easily verified that this is indeed true by making use of the inequalities (36) and (96) concerning $u$ and $c_1$ respectively.

A consequence of Sect. 6.3 is that if $c_1' := c_1 R^u$ satisfies (64), then all lines $L$ associated with intervals $\Delta(L) \in C_3(n, k, u, v)$ such that $\Delta(L) \cap J_{n-u} \neq \emptyset$ intersect at a single point. Inequality (64) is equivalent to

$$c_1 \leq \delta \cdot \frac{R^{1-\lambda i}}{2^k c_1^2} \quad \text{or} \quad c_1' \leq \delta \cdot \frac{R^{-\lambda i - \omega}}{2^k c_1^2}.$$ 

In view of (12), for $R$ large enough this upper bound inequality on $c$ is satisfied. Thus the coordinates $(A, B)$ associated with intervals $\Delta(L(A, B, C)) \in C_3(n, k, u, v)$ intersecting $J_{u,t}$ where $1 \leq t \leq d$, except possibly at most two, lie within the figure $F := F_t \cap F_v \cap L$.

We now follow the arguments from Part 1. If (85) is valid, then we deduce that the total number of intervals $I_{n+1} \subset J_n$ removed by intervals $\Delta(L)$ is bounded above by (99). Otherwise, the number $M$ of intervals $\Delta(L) \in C_3(n, k, u, v)$ that intersect $J_{u,t}$ with associated coordinates $(A, B) \in F$ can be estimated by (94). Thus, with $c_1' := c(k)$ given by (97) we obtain that

$$M \ll \left( \frac{2^k c_1^2 R^{1+i} R^u}{2^k Rc_1^2} \right)^{1/3} R^u(1-\min(\frac{j}{2}+\frac{i}{j}+\frac{i}{j})) \leq (R^c)^{1/3} \quad \text{if} \quad 2^k < R^{1-\omega}$$
and
\[ M \ll \left( \frac{2^k c^{\frac{1}{2}} R^{\omega+\epsilon} R^u}{R c^{\frac{1}{2}}} \right)^{1/i} R^{u(1-\min\{\frac{\lambda_j/(1+i)}{i}, \lambda_j\})} \leq (R^{\omega+\epsilon})^{1/i} \text{ if } 2^k \geq R^{1-\omega}. \]

Note that these are exactly the same estimates for \( M \) obtained in Part 3 above. Then as before, we deduce that the total number of intervals \( I_{n+1} \in \mathcal{I}_{n+1} \) with \( I_{n+1} \subset J_n \) removed by \( \Delta(L) \in C_3(n, k, u, v) \) is bounded above by \( R^{1-\epsilon} \). Hence, it follows that
\[ \# \{ I_{n+1} \in \mathcal{I}_{n+1} : I_{n+1} \subset J_{n-u}, \exists \Delta(L) \in \tilde{C}_3(n, u), \Delta(L) \cap I_{n+1} \neq \emptyset \} \ll \log^2 R \cdot R^{1-\epsilon}. \]

For \( R \) large enough the r.h.s. is bounded above by \( R^{1-\epsilon/2} \).

9 Proof of Theorem 2

The basic strategy of the proof of Theorem 1 also works for Theorem 2. The key is to establish the analogue of Theorem 3. In this section we outline the main differences and modifications. Let \((i, j)\) be a pair of real numbers satisfying (5). Given a line \( L_{\alpha, \beta} : x \to \alpha x + \beta \) we have that
\[ F_L(x) := (A - B\alpha)x + C - B\beta \quad \text{and} \quad V_L := |F'_L(x)| = |A - B\alpha|, \]
Thus, with in the context of Theorem 2 the quantity \( V_L \) is independent of \( x \). Furthermore, note that the Diophantine condition on \( \alpha \) implies that there exists an \( \epsilon > 0 \) such that
\[ V_L \gg B^{-1+\epsilon}. \] (102)
Also, \( |F''_L(x)| \equiv 0 \) and the analogue of Lemma 1 is the following statement.

**Lemma 6** There exists an absolute constant \( K \geq 1 \) dependent only on \( i, j, \alpha \) and \( \beta \) such that
\[ |\Delta(L)| \leq K \frac{c}{\max\{|A|^{1/i}, |B|^{1/j}\}} \cdot V_L. \]

A consequence of the lemma is that there are only Type 1 intervals to consider. Next note that for \( c \) small enough \( H(\Delta) > 1 \) for all intervals \( \Delta(L) \). Indeed
\[ H(\Delta) = c^{-1/2} V_L \max\{|A|^{1/i}, |B|^{1/j}\}. \]
So if \( |A| < \frac{|\alpha|}{2} |B| \), then \( V_L \propto B \) and \( H(\Delta) > 1 \) follows immediately. Otherwise,\[ H(\Delta) \gg c^{-1/2} \left( \frac{|A|}{|B|} \right)^{1/i} \]
which is also greater than 1 for \( c \) sufficiently small.
As in the case of non-degenerate curves, we partition the intervals $\Delta(L) \in \mathcal{R}$ into classes $C(n, k, l)$ according to (23) and (24). Unfortunately, we can not guarantee that $\lambda l \leq n$ as in the case of curves. However, we still have the bound $l \leq n$. To see that this is the case, suppose that $l > n$. Then (25) is satisfied and

$$|V_L| > R^{-\lambda n}(|\alpha| + 1) \max\{|A|, |B|\}. \quad (103)$$

By (23), we have that

$$R^{n-1} \leq H(\Delta) \leq R^n.$$

On combining the previous two displayed inequalities we get that

$$|A - \alpha B| \ll |B|^{\frac{i-\lambda}{1+i+\lambda}} \cdot (Rc^{1/2})^{\frac{\lambda}{1+\lambda}}.$$

Then by choosing $\lambda$ and $c$ such that

$$\lambda > \frac{i + 1}{\epsilon i} - 1 \quad \text{and} \quad (Rc^{1/2})^{\frac{\lambda}{1+\lambda}} < \inf_{q \in \mathbb{N}} \{q^{\frac{1}{1-\epsilon}} ||q\alpha||\} := \tau \quad (104)$$

implies that

$$|A - \alpha B| < \tau |B|^{-\frac{1}{1+\epsilon}}.$$

This contradicts the Diophantine condition imposed on $\alpha$ and so we must have that $l \leq n$.

With the above differences/changes in mind, it is possible to establish the analogue of Proposition 1 for lines $L_{\alpha, \beta}$ by following the same arguments and ideas as in the case of $C^{(2)}$ non-degenerate planar curves. The key differences in the analogous statement for lines is that in Part 1 we have $l \leq n$ instead of $\lambda l \leq n$ and that Part 2 disappears all together since there are no Type 2 intervals to consider. Recall, that even when establishing Proposition 1 for curves, Part 1, 3 and 4 only use the fact that the curve is two times differentiable—see Sect. 5 Remark 12. The analogue of Proposition 1 enables us to construct the appropriate Cantor set $K(J_0, R, r)$ which in turn leads to the desired analogue of Theorem 3.

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