

TITLE

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ACKNOWLEDGMENT

Will be added once thesis is finished

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF SYMBOLS	viii
ABSTRACT	ix
CHAPTER	
1. INTRODUCTION	1
2. PROBLEM STATEMENT AND ASSUMPTIONS	2
3. DATA-DRIVEN ERROR BOUND	5
3.1. Trapezoidal Rule	5
3.2. Simpson's Rule	6
4. ADAPTIVE, AUTOMATIC ALGORITHMS WITH GUARAN- TEES	8
4.1. Basic Concepts	8
4.2. Trapezoidal Rule	8
4.3. Simpson's Rule	9
5. COMPUTATIONAL COST OF GUARANTEED ALGORITHMS	10
5.1. Traezoidale rule	10
5.2. Simpson's rule	10
6. LOWER BOUND OF COMPLEXITY	13
6.1. Traezoidale rule	13
6.2. Simpson's rule	14
7. NUMERICAL EXPERIMENTS	18
7.1. Traezoidale rule	18

7.2. Simpson's Rule	19
8. CONCLUSION	20
8.1. Summary	20
APPENDIX	21
A. TABLE OF TRANSITION COEFFICIENTS FOR THE DESIGN OF LINEAR-PHASE FIR FILTERS	21
B. NAME OF YOUR SECOND APPENDIX	23
C. NAME OF YOUR THIRD APPENDIX	25

LIST OF TABLES

Table		Page
7.1	The probability of the test function lying in the cone for the original and eventual values of τ and the empirical success rate of Algorithm 1 plus the success rates of other common quadrature algorithms. .	19

LIST OF FIGURES

Figure	Page
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LIST OF SYMBOLS

Symbol	Definition
β	List of symbols will be added later

ABSTRACT

Abstract will be included once all parts are finished

CHAPTER 1

INTRODUCTION

Introduce existing algorithms for integration problems.

show drawbacks

1. Non-adaptive 2. adaptive no guarantees 3. maybe more

introduce

$$\text{INT}(f) = \int_a^b f(x)dx \in \mathbb{R}. \quad (1.1)$$

The goal is to construct adaptive, automatic algorithms with guarantees of success. In Chapter 2, I will introduce the definitions and assumptions used in the thesis. Chapter 3 will be focusing on finding the upper bound of the approximation errors. The guaranteed algorithms based on trapezoidal rule and Simpson's rule will be presented in Chapter 4 with rigorous theoretical proof of success/successfulness. Chapter 5 will study the lower and upper bound of computational cost. Chapter 6 will study the lower bound of complexity. In Chapter 7, the results from numerical experiences will be discussed.

CHAPTER 2

PROBLEM STATEMENT AND ASSUMPTIONS

The previous chapter introduced the univariate integration problem. The building blocks of the adaptive, automatic algorithms are two widely used fixed cost algorithms, trapezoidal rule and Simpson's rule. The composite trapezoidal rule can be defined as:

$$T(f, n) = \frac{b-a}{2n} \sum_{j=0}^n (f(u_j) + f(u_{j+1})), \quad (2.1)$$

where

$$u_j = a + \frac{j(b-a)}{n}, \quad j = 0, \dots, n, \quad n \in \mathbb{N}. \quad (2.2)$$

It uses $n+1$ function values where those $n+1$ node points are equally spaced between $[a, b]$. The composite Simpson's rule can be defined as:

$$S(f, n) = \frac{b-a}{12n} \sum_{j=0}^{6n-2} (f(v_j) + 4f(v_{j+1}) + f(v_{j+2})), \quad (2.3)$$

(double check index and fraction.) where

$$v_j = a + \frac{j(b-a)}{6n}, \quad j = 0, \dots, 6n, \quad n \in \mathbb{N}. \quad (2.4)$$

It uses $6n+1$ equally spaced function values, which form $6n$ intervals/subintervals between $[a, b]$. The reason why we use $6n$ intervals is that firstly, Simpson's rule requires an even number of intervals. Secondly, we are going to use the third order finite difference method to approximate the third derivative of f in later chapters. The third order finite difference method requires the number of intervals to be a multiple of 3. All in all, the number of intervals for input data has to be a multiple of 6.

We also need to find error bounds to guarantee our methods. If we look back at the traditional non-adaptive trapezoidal rule and Simpson's rule, the upper bound of

approximation error can be represented in terms of the total variation of a particular derivative of integrand.

$$\text{err}(f, n) \leq \overline{\text{err}}(f, n) := C(n) \text{Var}(f^{(p)}). \quad (2.5)$$

For trapezoidal rule, $C(n) = (b - a)^2/8n^2, p = 1$ (ref). For Simpson's rule, $C(n) = (b - a)^4/5832n^4, p = 3$ (ref).

To define the total variation, $\text{Var}(f)$, firstly we introduce the notation $\widehat{V}(f, \{x_i\}_{i=0}^{n+1})$ as an approximation to the total variation:

$$\widehat{V}(f, \{x_i\}_{i=0}^{n+1}) = \sum_{i=1}^{n-1} |f(x_{i+1}) - f(x_i)|, \quad (2.6)$$

where $\{x_i\}_{i=0}^{n+1}$ is any given partition with not necessarily equal spacing, and $a = x_0 \leq x_1 < \dots < x_n \leq x_{n+1} = b$. The use of $n + 2$ points is for convenience later. The total variation can be defined as an upper of bound of $\widehat{V}(f, \{x_i\}_{i=0}^{n+1})$:

$$\text{Var}(f) := \sup \left\{ \widehat{V}(f, \{x_i\}_{i=0}^{n+1}), \quad \text{for any } n \in \mathbb{N}, \text{ and } \{x_i\}_{i=0}^{n+1} \right\}, \quad (2.7)$$

To ensure finite error bound, our algorithms are defined for function spaces with finite total variations of the relative derivatives:

$$\mathcal{V}^p[a, b] := \{f \in C[a, b] : \text{Var}(f^{(p)}) < \infty\}, \quad (2.8)$$

where for trapezoidal rule, $p = 1$, and for Simpson's rule, $p = 3$.

Algorithms will not work for all $f \in \mathcal{V}^p$ because f may have changes in $f^{(p)}$ on small intervals that the algorithms cannot detect. In order to build an adaptive automatic and guaranteed algorithm, we have to set up the following pre-existing condition that all functions to be approximated must lie in a cone space of integrands for which $\widehat{V}(f, \{x_i\}_{i=0}^{n+1})$ does not underestimate $\text{Var}(f)$ too much:

$$\mathcal{C}^p := \left\{ f \in \mathcal{V}^p, \text{Var}(f^{(p)}) \leq \mathfrak{C}(\text{size}(\{x_i\}_{i=0}^{n+1})) \widehat{V}(f^{(p)}, \{x_i\}_{i=0}^{n+1}), \right. \\ \left. \text{for all choices of } n \in \mathbb{N}, \text{ and } \{x_i\}_{i=0}^{n+1} \text{ with } \text{size}(\{x_i\}_{i=0}^{n+1}) < \mathfrak{h} \right\}. \quad (2.9)$$

The cone space \mathcal{C}^p is a subspace of $\mathcal{V}^p[a, b]$. Here $\text{size}(\{x_i\}_{i=0}^{n+1})$ is the largest possible width between x_i . The cut-off value $\mathfrak{h} \in (0, b - a)$ and the inflation factor $\mathfrak{C} : [0, \mathfrak{h} \rightarrow [1, \infty)$ define the cone. The choice of \mathfrak{C} is flexible, but it must be non-decreasing. In this thesis, we choose $\mathfrak{C}(h) := \mathfrak{C}(0)\mathfrak{h}/(\mathfrak{h} - h)$.

With the cone space defined, we can start constructing our trapezoidal rule algorithm and Simpson's rule algorithm for functions in \mathcal{C}^p , with appropriate value of p . To begin with, Chapter 3 will show how the algorithms provide guarantees of success.

CHAPTER 3

DATA-DRIVEN ERROR BOUND

In this chapter, we will study the error bound of approximation errors. By (2.5) in Chapter 2, we know that the approximation errors of trapezoidal rule and Simpson's rule have an upper bound in terms of the total variation. Moreover, with the cone condition (2.9) defined, the total variation $\text{var}(f^{(p)})$ can be bounded by one of its approximation $\widehat{V}(f^{(p)}, \{x_i\}_{i=0}^{n+1})$. Definition of the cone suggests a way of bounding $\text{Var}(f^{(p)})$ in terms of $\widehat{V}(f^{(p)}, \{x_i\}_{i=0}^{n+1})$. However, the algorithm is based on function values and $\widehat{V}(f^{(p)}, \{x_i\}_{i=0}^{n+1})$ is determined in terms of derivative values. Thus we will use finite difference to express derivative values in terms of function values.

3.1 Trapezoidal Rule We used the backward finite difference method to approximate f' . Let $h = u_{j+1} - u_j = (b - a)/n$ and

$$\begin{aligned} f[u_j] &= f(u_j), \text{ for } j = 0, \dots, n, \\ f[u_j, u_{j-1}] &= \frac{f(u_j) - f(u_{j-1})}{h}, \text{ for } j = 1, \dots, n. \end{aligned}$$

According to Mean Value Theorem for divided differences, (ref), for all $j = 1, 2, \dots, n$, there exists $x_j \in (u_{j-1}, u_j)$ such that

$$f[u_j, u_{j-1}] = f'(x_j),$$

for $j = 1, 2, \dots, n$. This implies that

$$f'(x_j) = \frac{f(u_j) - f(u_{j-1})}{h} = \frac{n}{(b - a)} [f(u_j) - f(u_{j-1})], \quad (3.1)$$

for some $x_j \in (u_{j-1}, u_j)$. We will also obtain that no matter how the x_i 's are located, the largest possible width cannot be larger than two intervals. So $\text{size}(\{x_i\}_{i=0}^{n+1}) = 2h = 2(b - a)/n$.

Since (2.6) is true for all partition $\{x_i\}_{i=0}^{n+1}$, it is true for (3.1). Then we have the approximation $\tilde{V}_1(f, n)$ to $\widehat{V}(f^{(p)}, \{x_i\}_{i=0}^{n+1})$ using only function values:

$$\tilde{V}_1(f, n) := \frac{n}{(b-a)} \sum_{j=1}^{n-1} |f(u_{j+1}) - 2f(u_j) + f(u_{j-1})| = \widehat{V}(f', \{x_i\}_{i=0}^{n+1}). \quad (3.2)$$

Therefore by combining (2.5), (2.9), and (3.2) together, we will obtain the error bound for our trapezoidal rule algorithm using only function values:

$$\begin{aligned} \overline{\text{err}}(f, n) &:= C(n) \text{Var}(f^{(p)}), \\ &\leq C(n) \mathfrak{C}(\text{size}(\{x_i\}_{i=0}^{n+1})) \widehat{V}(f^{(p)}, \{x_i\}_{i=0}^{n+1}), \\ &= C(n) \mathfrak{C}(\text{size}(\{x_i\}_{i=0}^{n+1})) \tilde{V}_1(f, n), \\ &= \frac{(b-a)^2 \mathfrak{C}(2(b-a)/n) \tilde{V}_1(f, n)}{8n} \end{aligned}$$

(fix equation number)

This error bound of our algorithm using only function values provides guarantees that it will succeed. With a user provided tolerance ε , as long as n is big enough, the approximation error will eventually decrease below ε .

3.2 Simpson's Rule

From (2.5) in Chapter 2, we know that the error bound of approximations using Simpson's rule can be bounded by the variation of the third derivatives of the function. We do not have the variation of the third derivatives of the function. In order to find the error bound, we introduced the cone space of input functions so that the approximation error of functions within the space can be bounded by $\widehat{V}(f''', \{x_i\}_{i=0}^{n+1})$. However, we cannot use $\widehat{V}(f''', \{x_i\}_{i=0}^{n+1})$ to approximate $\text{Var}(f''')$ because it depends on values of f''' , not values of f . In this case, we consider the

following approximation to $\text{Var}(f''')$ which is closely related to $\widehat{V}(f''', \{x_i\}_{i=0}^{n+1})$:

$$\begin{aligned} \widetilde{V}_n(f) = \frac{216n^3}{(b-a)^3} \sum_{j=1}^{2n-1} & |f(v_{3j+3}) - 3f(v_{3j+2}) + 3f(v_{3j+1}) \\ & - 2f(v_{3j}) + 3f(v_{3j-1}) - 3f(v_{3j-2}) + f(v_{3j-3})|, \quad (3.3) \end{aligned}$$

We use divided differences to explain The relationship between (2.6) and (??).

Let $h = v_{j+1} - v_j = (b-a)/6n$ and

$$\begin{aligned} f[v_j] &= f(v_j), \text{ for } j = 0, \dots, 6n, \\ f[v_j, v_{j-1}] &= \frac{f(v_j) - f(v_{j-1})}{h}, \text{ for } j = 1, \dots, 6n, \\ f[v_j, v_{j-1}, v_{j-2}] &= \frac{f(v_j) - 2f(v_{j-1}) + f(v_{j-2})}{2h^2}, \text{ for } j = 2, \dots, 6n, \\ f[v_j, v_{j-1}, v_{j-2}, v_{j-3}] &= \frac{f(v_j) - 3f(v_{j-1}) + 3f(v_{j-2}) - f(v_{j-3})}{6h^3}, \text{ for } j = 3, \dots, 6n. \end{aligned}$$

According to Mean Value Theorem for divided differences, (ref), for all $j = 1, 2, \dots, n$, there exists $x_j \in (v_{3j-3}, v_{3j})$ such that

$$f[v_{3j}, v_{3j-1}, v_{3j-2}, v_{3j-3}] = \frac{f'''(x_j)}{6},$$

for $j = 1, 2, \dots, n$. This implies that

$$\begin{aligned} f'''(x_j) &= \frac{f(v_{3j}) - 3f(v_{3j-1}) + 3f(v_{3j-2}) - f(v_{3j-3})}{h^3}, \\ &= \frac{216n^3}{(b-a)^3} [f(v_{3j}) - 3f(v_{3j-1}) + 3f(v_{3j-2}) - f(v_{3j-3})]. \quad (3.4) \end{aligned}$$

If we combine (??) and (3.4) together, we obtain

$$\widetilde{V}_n(f) = \sum_{j=1}^{n-1} |f'''(x_{j+1}) - f'''(x_j)| = \widehat{V}(f''', \{x_j\}_{j=0}^{n+1}). \quad (3.5)$$

Then we can use $\widetilde{V}_n(f)$ to approximate $\text{Var}(f''')$ by just using function values.

(Add the formula here.)

CHAPTER 4

ADAPTIVE, AUTOMATIC ALGORITHMS WITH GUARANTEES

4.1 Basic Concepts AA I need to explain the embedded mechanism and stopping criteria with tolerance, max iteration and max number of points. In the following subsections, I need detailed explanation of the algorithms.

4.2 Trapezoidal Rule

Algorithm 1 (Adaptive Univariate Integration). Let the sequence of algorithms $\{T_n\}_{n \in \mathcal{I}}$, $\{\tilde{F}_n\}_{n \in \mathcal{I}}$, and $\{F_n\}_{n \in \mathcal{I}}$ be as described above. Let $\tau \geq 2$ be the cone constant. Set $i = 1$. Let $n_1 = \lceil (\tau + 1)/2 \rceil + 1$. For any error tolerance ε and input function f , do the following:

Stage 1. Estimate $\|f' - f(1) + f(0)\|_1$ **and bound** $\text{Var}(f')$. Compute $\tilde{F}_{n_i}(f)$ in (??) and $F_{n_i}(f)$ in (??).

Stage 2. Check the necessary condition for $f \in \mathcal{C}_\tau$. Compute

$$\tau_{\min, n_i} = \frac{F_{n_i}(f)}{\tilde{F}_{n_i}(f) + F_{n_i}(f)/(2n_i - 2)}.$$

If $\tau \geq \tau_{\min, n_i}$, then go to stage 3. Otherwise, set $\tau = 2\tau_{\min, n_i}$. If $n_i \geq (\tau + 1)/2$, then go to stage 3. Otherwise, choose

$$n_{i+1} = 1 + (n_i - 1) \left\lceil \frac{\tau + 1}{2n_i - 2} \right\rceil.$$

Go to Stage 1.

Stage 3. Check for convergence. Check whether n_i is large enough to satisfy the error tolerance, i.e.

$$\tilde{F}_{n_i}(f) \leq \frac{4\varepsilon(n_i - 1)(2n_i - 2 - \tau)}{\tau}.$$

If this is true, then return $T_{n_i}(f)$ and terminate the algorithm. If this is not true, choose

$$n_{i+1} = 1 + (n_i - 1) \max \left\{ 2, \left\lceil \frac{1}{(n_i - 1)} \sqrt{\frac{\tau \tilde{F}_{n_i}(f)}{8\varepsilon}} \right\rceil \right\}.$$

Go to Stage 1.

4.3 Simpson's Rule

Algorithm 2 (Adaptive Univariate Integration). Given an interval $[a, b]$, an inflation function, \mathfrak{C} , a positive key mesh size \mathfrak{h} , a positive error tolerance, ε , and a routine for generating values of the integrand, f , set $l = 1$, and $n_1 = 2(\lfloor (b - a)/\mathfrak{h} \rfloor + 1)$.

Stage 1 Compute the error estimate $\widetilde{\text{err}}(f, n_l)$ according to (??).

Stage 2 If $\widetilde{\text{err}}(f, n_l) \leq \varepsilon$, then return the Simpson's rule approximation $S_{n_l}(f)$ as the answer.

Stage 3 Otherwise let $n_{l+1} = \max(2, m)\eta_l$, where

$$m = \min\{r \in \mathbb{N} : \eta(r n_l) \tilde{V}_{n_l(f)} \leq \varepsilon\}, \text{ with } \eta(n) := \frac{(b - a)^4 \mathfrak{C}(2(b - a)/n)}{5832n^4}.$$

increase l by one, and go to 1.

Theorem 1. *Algorithm 2 is successful, i.e.,*

$$\left| \int_a^b f(x) dx - \text{integral}(f, a, b, \varepsilon) \right| \leq \varepsilon, \quad \forall f \in \mathcal{C}.$$

CHAPTER 5

COMPUTATIONAL COST OF GUARANTEED ALGORITHMS

5.1 Traezoidale rule

Theorem 2. *Let $\sigma > 0$ be some fixed parameter, and let $\mathcal{B}_\sigma = \{f \in \mathcal{V}^1 : \text{Var}(f') \leq \sigma\}$. Let $T \in \mathcal{A}(\mathcal{B}_\sigma, \mathbb{R}, \text{INT}, \Lambda^{\text{std}})$ be the non-adaptive trapezoidal rule defined by Algorithm ??, and let $\varepsilon > 0$ be the error tolerance. Then this algorithm succeeds for $f \in \mathcal{B}_\sigma$, i.e., $|\text{INT}(f) - T(f, \varepsilon)| \leq \varepsilon$, and the cost of this algorithm is $\left\lceil \sqrt{\sigma/(8\varepsilon)} \right\rceil + 1$, regardless of the size of $\text{Var}(f')$.*

Now let $T \in \mathcal{A}(\mathcal{C}_\tau, \mathbb{R}, \text{INT}, \Lambda^{\text{std}})$ be the adaptive trapezoidal rule defined by Algorithm 1, and let τ , n_1 , and ε be as described there. Let \mathcal{C}_τ be the cone of functions defined in (??). Then it follows that Algorithm 1 is successful for all functions in \mathcal{C}_τ , i.e., $|\text{INT}(f) - T(f, \varepsilon)| \leq \varepsilon$. Moreover, the cost of this algorithm is bounded below and above as follows:

$$\begin{aligned}
& \max \left(\left\lceil \frac{\tau+1}{2} \right\rceil, \left\lceil \sqrt{\frac{\text{Var}(f')}{8\varepsilon}} \right\rceil \right) + 1 \\
& \leq \max \left(\left\lceil \frac{\tau+1}{2} \right\rceil, \left\lceil \sqrt{\frac{\tau \|f' - f(1) + f(0)\|_1}{8\varepsilon}} \right\rceil \right) + 1 \\
& \leq \text{cost}(T, f; \varepsilon) \\
& \leq \sqrt{\frac{\tau \|f' - f(1) + f(0)\|_1}{2\varepsilon}} + \tau + 4 \leq \sqrt{\frac{\tau \text{Var}(f')}{4\varepsilon}} + \tau + 4. \quad (5.1)
\end{aligned}$$

The algorithm is computationally stable, meaning that the minimum and maximum costs for all integrands, f , with fixed $\|f' - f(1) + f(0)\|_1$ or $\text{Var}(f')$ are an ε -independent constant of each other.

5.2 Simpson's rule

Theorem 3. *Let $N(f, \varepsilon)$ denote the final number of n_l in Stage 2 when the algorithm terminates. Then this number is bounded below and above in terms of the true, yet*

unknown, $\text{Var}(f''')$.

$$\begin{aligned}
& \max \left(\left\lfloor \frac{2(b-a)}{\mathfrak{h}} \right\rfloor + 1, \left\lceil (b-a) \left(\frac{\text{Var}(f''')}{5832\varepsilon} \right)^{1/4} \right\rceil \right) \leq N(f, \varepsilon) \\
& \leq 2 \min \left\{ n \in \mathbb{N} : n \geq 2 \left(\left\lfloor \frac{(b-a)}{\mathfrak{h}} \right\rfloor + 1 \right), \eta(n) \text{Var}(f''') \leq \varepsilon \right\} \\
& \leq 2 \min_{0 < \alpha \leq 1} \max \left(2 \left(\left\lfloor \frac{(b-a)}{\alpha \mathfrak{h}} \right\rfloor + 1 \right), (b-a) \left(\frac{\mathfrak{C}(\alpha \mathfrak{h}) \text{Var}(f''')}{5832\varepsilon} \right)^{1/4} + 1 \right). \quad (5.2)
\end{aligned}$$

The number of function values required by the algorithm is $3N(f, \varepsilon) + 1$.

Proof. No matter what inputs f and ε are provided, $N(f, \varepsilon) \geq n_1 = 2(\lfloor (b-a)/\mathfrak{h} \rfloor + 1)$. Then the number of intervals increases until $\widetilde{\text{err}}(f, n) \leq \varepsilon$, which by (??) implies that $\overline{\text{err}}(f, n) \leq \varepsilon$. This implies the lower bound on $N(f, \varepsilon)$.

Let L be the value of l for which Algorithm 2 terminates. Since n_1 satisfies the upper bound, we may assume that $L \geq 2$. Let m be the integer found in Step 3, and let $m^* = \max(2, m)$. Note that $\eta((m^*-1)n_{L-1}) \text{Var}(f''') > \varepsilon$. For $m^* = 2$, this is true because $\eta(n_{L-1}) \text{Var}(f''') \geq \eta(n_{L-1}) \widetilde{V}_{n_{L-1}}(f) = \widetilde{\text{err}}(f, n_{L-1}) > \varepsilon$. For $m^* = m > 2$ it is true because of the definition of m . Since η is a decreasing function, it follows that

$$(m^* - 1)n_{L-1} < n^* := \min \left\{ n \in \mathbb{N} : n \geq \left\lfloor \frac{2(b-a)}{n} \right\rfloor + 1, \eta(n) \text{Var}(f''') \leq \varepsilon \right\}.$$

Therefore $n_L = m^* n_{L-1} < m^* \frac{n^*}{m^*-1} = \frac{m^*}{m^*-1} n^* \leq 2n^*$.

To prove the latter part of the upper bound, we need to prove that

$$n^* \leq \max \left(\left\lfloor \frac{2(b-a)}{\alpha \mathfrak{h}} \right\rfloor + 1, (b-a) \left(\frac{\mathfrak{C}(\alpha \mathfrak{h}) \text{Var}(f''')}{5832\varepsilon} \right)^{1/4} + 1 \right), \quad 0 < \alpha < 1.$$

For fixed $\alpha \in (0, 1]$, we only need to consider that case where $n^* > \lfloor 2(b-a)/(\alpha \mathfrak{h}) \rfloor + 1$.

This implies that $n^* - 1 > \lfloor 2(b-a)/(\alpha \mathfrak{h}) \rfloor \geq 2(b-a)/(\alpha \mathfrak{h})$ thus $\alpha \mathfrak{h} \geq 2(b-a)/(n^* - 1)$.

Also by the definition of n^* , η , and \mathfrak{C} is non-decreasing:

$$\begin{aligned}
& \eta(n^* - 1) \operatorname{Var}(f''') > \varepsilon, \\
& \Rightarrow 1 < \left(\frac{\eta(n^* - 1) \operatorname{Var}(f''')}{\varepsilon} \right)^{1/4}, \\
& \Rightarrow n^* - 1 < n^* - 1 \left(\frac{\eta(n^* - 1) \operatorname{Var}(f''')}{\varepsilon} \right)^{1/4}, \\
& = n^* - 1 \left(\frac{(b - a)^4 \mathfrak{C}(2(b - a)/(n^* - 1)) \operatorname{Var}(f''')}{5832(n^* - 1)^4 \varepsilon} \right)^{1/4}, \\
& \leq (b - a) \left(\frac{\mathfrak{C}(\alpha \mathfrak{h}) \operatorname{Var}(f''')}{5832 \varepsilon} \right)^{1/4}.
\end{aligned}$$

This completes the prove of latter part of the upper bound. □

CHAPTER 6

LOWER BOUND OF COMPLEXITY

6.1 Traezoidale rule Next, we derive a lower bound on the cost of approximating functions in the ball \mathcal{B}_σ and in the cone \mathcal{C}_τ by constructing fooling functions. Following the arguments of Section ??, we choose the triangle shaped function $f_0 : x \mapsto 1/2 - |1/2 - x|$. Then

$$|f_0|_{\mathcal{F}} = \|f'_0 - f_0(1) + f_0(0)\|_1 = \int_0^1 |\text{sign}(1/2 - x)| \, dx = 1,$$

$$|f_0|_{\mathcal{F}} = \text{Var}(f'_0) = 2 = \tau_{\min}.$$

For any $n \in \mathcal{J} := \mathbb{N}_0$, suppose that the one has the data $L_i(f) = f(\xi_i)$, $i = 1, \dots, n$ for arbitrary ξ_i , where $0 = \xi_0 \leq \xi_1 < \dots < \xi_n \leq \xi_{n+1} = 1$. There must be some $j = 0, \dots, n$ such that $\xi_{j+1} - \xi_j \geq 1/(n+1)$. The function f_1 is defined as a triangle function on the interval $[\xi_j, \xi_{j+1}]$:

$$f_1(x) := \begin{cases} \frac{\xi_{j+1} - \xi_j - |\xi_{j+1} + \xi_j - 2x|}{8} & \xi_j \leq x \leq \xi_{j+1}, \\ 0 & \text{otherwise.} \end{cases}$$

This is a piecewise linear function whose derivative changes from 0 to $1/4$ to $-1/4$ to 0 provided $0 < \xi_j < \xi_{j+1} < 1$, and so $|f_1|_{\mathcal{F}} = \text{Var}(f'_1) \leq 1$. Moreover,

$$\text{INT}(f) = \int_0^1 f_1(x) \, dx = \frac{(\xi_{j+1} - \xi_j)^2}{16} \geq \frac{1}{16(n+1)^2} =: g(n),$$

$$g^{-1}(\varepsilon) = \left\lceil \sqrt{\frac{1}{16\varepsilon}} \right\rceil - 1.$$

Using these choices of f_0 and f_1 , along with the corresponding g above, one may invoke Theorems ??–??, and Corollary ?? to obtain the following theorem.

Theorem 4. *For $\sigma > 0$ let $\mathcal{B}_\sigma = \{f \in \mathcal{V}^1 : \text{Var}(f') \leq \sigma\}$. The complexity of integration on this ball is bounded below as*

$$\text{comp}(\varepsilon, \mathcal{A}(\mathcal{B}_\sigma, \mathbb{R}, \text{INT}, \Lambda^{\text{std}}), \mathcal{B}_s) \geq \left\lceil \sqrt{\frac{\min(s, \sigma)}{16\varepsilon}} \right\rceil - 1.$$

Algorithm ?? using the trapezoidal rule has optimal order in the sense of Theorem ??.

For $\tau > 2$, the complexity of the integration problem over the cone of functions \mathcal{C}_τ defined in (??) is bounded below as

$$\text{comp}(\varepsilon, \mathcal{A}(\mathcal{C}_\tau, \mathbb{R}, \text{INT}, \Lambda^{\text{std}}), \mathcal{B}_s) \geq \left\lceil \sqrt{\frac{(\tau - 2)s}{32\tau\varepsilon}} \right\rceil - 1.$$

The adaptive trapezoidal Algorithm 1 has optimal order for integration of functions in \mathcal{C}_τ in the sense of Corollary ??.

6.2 Simpson's rule building fooling function:

$$\text{bump}(x; t, h) := \begin{cases} (x - t)^3/6, & t \leq x < t + h, \\ [-3(x - t)^3 + 12h(x - t)^2 - 12h^2(x - t) + 4h^3]/6, & t + h \leq x < t + 2h, \\ [3(x - t)^3 - 24h(x - t)^2 + 60h^2(x - t) - 44h^3]/6, & t + 2h \leq x < t + 3h, \\ (t + 4h - x)^3/6, & t + 3h \leq x < t + 4h, \\ 0, & \text{otherwise,} \end{cases} \quad (6.1a)$$

$$\text{bump}'''(x; t, h) := \begin{cases} 1, & t \leq x < t + h, \\ -3, & t + h \leq x < t + 2h, \\ 3, & t + 2h \leq x < t + 3h, \\ -1, & t + 3h \leq x < t + 4h, \\ 0, & \text{otherwise,} \end{cases} \quad (6.1b)$$

$$\text{Var}(\text{bump}'''(\cdot; t, h)) \leq 16 \text{ with equality if } a < t < t + 4h < b, \quad (6.1c)$$

$$\int_a^b \text{peak}(x; t, h) dx = h^4. \quad (6.1d)$$

The following double-bump function always lies in \mathcal{C} :

$$\begin{aligned} \text{twobp}(x; t, h, \pm) &:= \text{bump}(x; a, \mathfrak{h}) \pm \frac{15[\mathfrak{C}(h) - 1]}{16} \text{bump}(x; t, h) \\ a + 5\mathfrak{h} &\leq h \leq b - 5h, 0 \leq h < \mathfrak{h}. \end{aligned} \quad (6.2a)$$

$$\text{Var}(\text{twobp}'''(x; t, h, \pm)) = 15 + 16 \frac{15[\mathfrak{C}(h) - 1]}{16} = 15\mathfrak{C}(h). \quad (6.2b)$$

From this definition it follows that

$$\begin{aligned} &\mathfrak{C}(\text{size}(\{x_j\}_{j=0}^{n+1})) \widehat{V}(\text{twobp}'''(x; t, h, \pm), \{x_j\}_{j=0}^{n+1}) \\ &\geq \begin{cases} 15\mathfrak{C}(h) = \text{Var}(\text{twobp}'''(x; t, h, \pm)), h \leq \text{size}(\{x_j\}_{j=0}^{n+1}) < \mathfrak{h} \\ \mathfrak{C}(0) \text{Var}(\text{twobp}'''(x; t, h, \pm)), 0 \leq \text{size}(\{x_j\}_{j=0}^{n+1}) < h \end{cases} \\ &\geq \text{Var}(\text{twobp}'''(x; t, h, \pm)) \end{aligned}$$

Although $\text{twobp}'''(x; t, h, \pm)$ may have a bump with arbitrarily small width $4h$, the height is small enough for $\text{twobp}'''(x; t, h, \pm)$ to lie in the cone.

complexity:

Theorem 5. *Let int be any (possibly adaptive) algorithm that succeeds for all integrands in \mathcal{C} , and only uses function values. For any error tolerance $\varepsilon > 0$ and any arbitrary value of $\text{Var}(f''')$, there will be some $f \in \mathcal{C}$ for which int must use at least*

$$-\frac{5}{4} + \frac{b - a - 5\mathfrak{h}}{8} \left[\frac{[\mathfrak{C}(0) - 1] \text{Var}(f''')}{\varepsilon} \right]^{1/4} \quad (6.3)$$

*function values. As $\text{Var}(f''')/\varepsilon \rightarrow \infty$ the asymptotic rate of increase is the same as the computational cost of **integral**.*

Proof. For any positive α , suppose that $\text{int}(\cdot, a, b, \varepsilon)$ evaluates integrand $\alpha \text{bump}'''(\cdot; t, h)$ at n nodes before returning to an answer. Let $\{x_j\}_{j=1}^m$ be the $m < n$ ordered

nodes used by $\text{int}(\cdot, a, b, \varepsilon)$ that fall in the interval (x_0, x_{m+1}) where $x_0 := a + 3\mathfrak{h}$, $x_{m+1} := b - h$ (why h but not \mathfrak{h} or $5h$?) and $h := (b - a - 5\mathfrak{h})/(4n + 5)$. There must be at least one of these x_j with $i = 0, \dots, m$ for which

$$\frac{x_{j+1} - x_j}{4} \geq \frac{x_{m+1} - x_0}{4(m+1)} \geq \frac{x_{m+1} - x_0}{4(n+1)} = \frac{b - a - 5\mathfrak{h} - h}{4n + 4} = h.$$

Choose one such x_j and call it t . The choice of t and h ensures that $\text{int}(\cdot, a, b, \varepsilon)$ cannot distinguish between $\alpha\text{bump}(\cdot; t, h)$ and $\alpha\text{twobp}(\cdot; t, h, \pm)$. Thus

$$\text{int}(\alpha\text{twobp}(\cdot; t, h, \pm), a, b, \varepsilon) = \text{int}(\alpha\text{bump}(\cdot; t, h), a, b, \varepsilon)$$

Moreover, $\alpha\text{bump}(\cdot; t, h)$ and $\alpha\text{twobp}(\cdot; t, h, \pm)$ are all in the cone \mathcal{C} . This means that int is successful for all of the functions.

$$\begin{aligned} \varepsilon &\geq \frac{1}{2} \left[\left| \int_a^b \alpha\text{twobp}(x; t, h, -) dx - \text{int}(\alpha\text{twobp}(\cdot; t, h, -), a, b, \varepsilon) \right| \right. \\ &\quad \left. + \left| \int_a^b \alpha\text{twobp}(x; t, h, +) dx - \text{int}(\alpha\text{twobp}(\cdot; t, h, +), a, b, \varepsilon) \right| \right] \\ &\geq \frac{1}{2} \left[\left| \text{int}(\alpha\text{bump}(\cdot; t, h, -), a, b, \varepsilon) - \int_a^b \alpha\text{twobp}(x; t, h, -) dx \right| \right. \\ &\quad \left. + \left| \int_a^b \alpha\text{twobp}(x; t, h, +) dx - \text{int}(\alpha\text{bump}(\cdot; t, h, +), a, b, \varepsilon) \right| \right] \\ &\geq \frac{1}{2} \left| \int_a^b \alpha\text{twobp}(x; t, h, +) dx - \int_a^b \alpha\text{twobp}(x; t, h, -) dx \right| \\ &= \int_a^b \alpha\text{bump}(x; t, h) dx \\ &= \frac{15\alpha[\mathfrak{C}(h) - 1]h^4}{16} \\ &= \frac{[\mathfrak{C}(h) - 1]h^4 \text{Var}(\alpha\text{bump}'''(\cdot; a, \mathfrak{h}))}{16} \end{aligned}$$

Substituting h in terms of n :

$$\begin{aligned} 4n + 5 = \frac{b - a - 5\mathfrak{h}}{h} &\geq (b - a - 5\mathfrak{h}) \left[\frac{[\mathfrak{C}(h) - 1] \text{Var}(\alpha\text{bump}'''(\cdot; a, \mathfrak{h}))}{16\varepsilon} \right]^{1/4}, \\ &\geq \frac{b - a - 5\mathfrak{h}}{2} \left[\frac{[\mathfrak{C}(0) - 1] \text{Var}(\alpha\text{bump}'''(\cdot; a, \mathfrak{h}))}{\varepsilon} \right]^{1/4}. \end{aligned}$$

Since α is an arbitrary positive number, the value of $\text{Var}(\alpha \mathbf{bump}'''(\cdot; a, \mathfrak{h}))$ is arbitrary.

Finally, comparing the upper bound on the computational cost of `integral` in (5.2) with the lower bound on the computational cost of the best algorithm in (6.3), both of them increase as $\mathcal{O}((\text{Var}(f''')/\varepsilon))^{1/4}$ as $(\text{Var}(f''')/\varepsilon)^{1/4} \rightarrow \infty$. Thus `integral` is optimal. \square

CHAPTER 7

NUMERICAL EXPERIMENTS

7.1 Traezoidale rule Consider the family of bump test functions defined by

$$f(x) = \begin{cases} b[4a^2 + (x - z)^2 + (x - z - a)|x - z - a| \\ \quad - (x - z + a)|x - z + a|], & z - 2a \leq x \leq z + 2a, \\ 0, & \text{otherwise.} \end{cases} \quad (7.1)$$

with $\log_{10}(a) \sim \mathcal{U}[-4, -1]$, $z \sim \mathcal{U}[2a, 1 - 2a]$, and $b = 1/(4a^3)$ chosen to make $\int_0^1 f(x) dx = 1$. It follows that $\|f' - f(1) + f(0)\|_1 = 1/a$ and $\text{Var}(f') = 2/a^2$. The probability that $f \in \mathcal{C}_\tau$ is $\min(1, \max(0, (\log_{10}(\tau/2) - 1)/3))$.

As an experiment, we chose 10000 random test functions and applied Algorithm 1 with an error tolerance of $\varepsilon = 10^{-8}$ and initial τ values of 10, 100, 1000. The algorithm is considered successful for a particular f if the exact and approximate integrals agree to within ε . The success and failure rates are given in Table 7.1. Our algorithm imposes a cost budget of $N_{\max} = 10^7$. If the proposed n_{i+1} in Stages 2 or 3 exceeds N_{\max} , then our algorithm returns a warning and falls back to the largest possible n_{i+1} not exceeding N_{\max} for which $n_{i+1} - 1$ is a multiple of $n_i - 1$. The probability that f initially lies in \mathcal{C}_τ is the smaller number in the third column of Table 7.1, while the larger number is the empirical probability that f eventually lies in \mathcal{C}_τ after possible increases in τ made by Stage 2 of Algorithm 1. For this experiment Algorithm 1 was successful for all f that finally lie inside \mathcal{C}_τ and for which no attempt was made to exceed the cost budget.

Some commonly available numerical algorithms in MATLAB are `quad` and `integral` [?] and the MATLAB Chebfun toolbox [?]. We applied these three routines

			Success	Success	Failure
			No Warning	Warning	No Warning
	τ	$\text{Prob}(f \in \mathcal{C}_\tau)$			
Algorithm 1	10	0% \rightarrow 25%	25%	< 1%	75%
	100	23% \rightarrow 58%	56%	2%	42%
	1000	57% \rightarrow 88%	68%	20%	12%
quad			8%		92%
integral			19%		81%
chebfun			29%		71%

Table 7.1. The probability of the test function lying in the cone for the original and eventual values of τ and the empirical success rate of Algorithm 1 plus the success rates of other common quadrature algorithms.

to the random family of test functions. Their success and failure rates are also recorded in Table 7.1. They do not give warnings of possible failure.

7.2 Simpson's Rule I need to use a good example to run the tests. Then I will need to compare the results for both algorithms with other algorithms. After that, I need to compare trap and sim to get the conclusion such as sim has faster convergence rate than trap. This will require an sample function good to both trap and sim.

CHAPTER 8

CONCLUSION

A

8.1 Summary

A

APPENDIX A
TABLE OF TRANSITION COEFFICIENTS FOR THE DESIGN OF
LINEAR-PHASE FIR FILTERS

Your Appendix will go here !

APPENDIX B
NAME OF YOUR SECOND APPENDIX

Your second appendix text....

APPENDIX C
NAME OF YOUR THIRD APPENDIX

Your third appendix text....