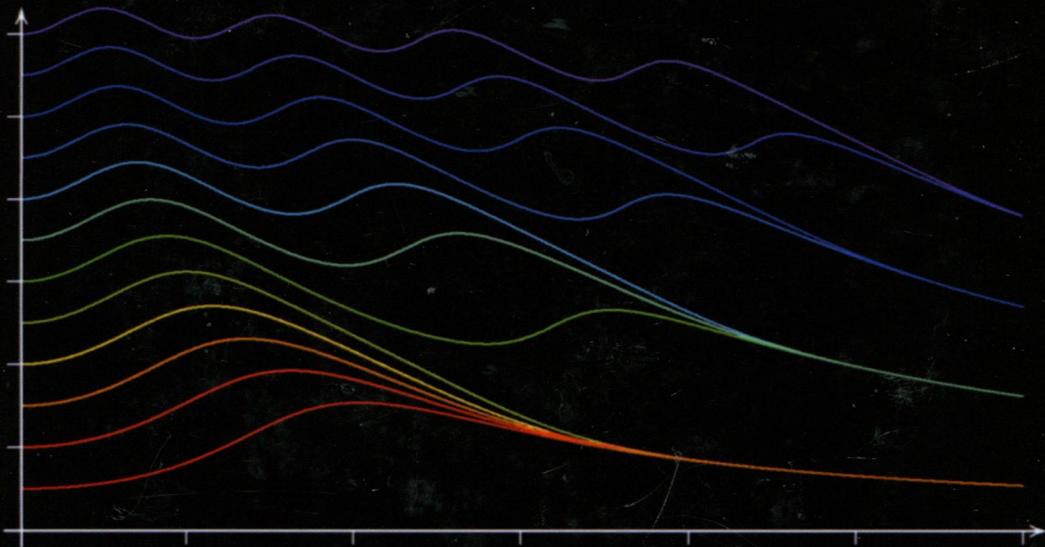


# Asymptotic Analysis and Perturbation Theory



**William Paulsen**

 **CRC Press**  
Taylor & Francis Group

A CHAPMAN & HALL BOOK

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2014 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper  
Version Date: 20130524

International Standard Book Number-13: 978-1-4665-1511-6 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

**Visit the Taylor & Francis Web site at**  
**<http://www.taylorandfrancis.com>**

**and the CRC Press Web site at**  
**<http://www.crcpress.com>**

---

# Contents

List of Figures	ix
List of Tables	xiii
Preface	xv
Acknowledgments	xvii
About the Author	xix
Symbol Description	xxi
<b>1 Introduction to Asymptotics</b>	<b>1</b>
1.1 Basic Definitions . . . . .	1
1.1.1 Definition of $\sim$ and $\ll$ . . . . .	1
1.1.2 Hierarchy of Functions . . . . .	4
1.1.3 Big $O$ and Little $o$ Notation . . . . .	6
1.2 Limits via Asymptotics . . . . .	8
1.3 Asymptotic Series . . . . .	13
1.4 Inverse Functions . . . . .	22
1.4.1 Reversion of Series . . . . .	26
1.5 Dominant Balance . . . . .	30
<b>2 Asymptotics of Integrals</b>	<b>37</b>
2.1 Integrating Taylor Series . . . . .	37
2.2 Repeated Integration by Parts . . . . .	44
2.2.1 Optimal asymptotic approximation . . . . .	48
2.3 Laplace's Method . . . . .	53
2.3.1 Properties of $\Gamma(x)$ . . . . .	59
2.3.2 Watson's Lemma . . . . .	61
2.4 Review of Complex Numbers . . . . .	69
2.4.1 Analytic Functions . . . . .	73
2.4.2 Contour Integration . . . . .	77
2.4.3 Gevrey Asymptotics . . . . .	80
2.4.4 Asymptotics for Oscillatory Functions . . . . .	84
2.5 Method of Stationary Phase . . . . .	90
2.6 Method of Steepest Descents . . . . .	97
2.6.1 Saddle Points . . . . .	101

<b>3</b>	<b>Speeding Up Convergence</b>	<b>111</b>
3.1	Shanks Transformation . . . . .	111
3.1.1	Generalized Shanks Transformation . . . . .	114
3.2	Richardson Extrapolation . . . . .	117
3.2.1	Generalized Richardson Extrapolation . . . . .	120
3.3	Euler Summation . . . . .	124
3.4	Borel Summation . . . . .	130
3.4.1	Generalized Borel Summation . . . . .	132
3.4.2	Stieltjes Series . . . . .	137
3.5	Continued Fractions . . . . .	144
3.6	Padé Approximants . . . . .	154
3.6.1	Two-point Padé . . . . .	158
<b>4</b>	<b>Differential Equations</b>	<b>163</b>
4.1	Classification of Differential Equations . . . . .	163
4.1.1	Linear vs. Non-Linear . . . . .	166
4.1.2	Homogeneous vs. Inhomogeneous . . . . .	168
4.1.3	Initial Conditions vs. Boundary Conditions . . . . .	173
4.1.4	Regular Singular Points vs. Irregular Singular Points . . . . .	175
4.2	First Order Equations . . . . .	181
4.2.1	Separable Equations . . . . .	181
4.2.2	First Order Linear Equations . . . . .	184
4.3	Taylor Series Solutions . . . . .	187
4.4	Frobenius Method . . . . .	197
<b>5</b>	<b>Asymptotic Series Solutions for Differential Equations</b>	<b>207</b>
5.1	Behavior for Irregular Singular Points . . . . .	207
5.2	Full Asymptotic Expansion . . . . .	217
5.3	Local Analysis of Inhomogeneous Equations . . . . .	228
5.3.1	Variation of Parameters . . . . .	234
5.4	Local Analysis for Non-linear Equations . . . . .	243
<b>6</b>	<b>Difference Equations</b>	<b>253</b>
6.1	Classification of Difference Equations . . . . .	253
6.1.1	Anti-differences . . . . .	256
6.1.2	Regular and Irregular Singular Points . . . . .	259
6.2	First Order Linear Equations . . . . .	263
6.2.1	Solving General First Order Linear Equations . . . . .	265
6.2.2	The Digamma Function . . . . .	269
6.3	Analysis of Linear Difference Equations . . . . .	274
6.3.1	Full Stirling Series . . . . .	278
6.3.2	Taylor Series Solution . . . . .	281
6.4	The Euler-Maclaurin Formula . . . . .	286
6.4.1	The Bernoulli Numbers . . . . .	289
6.4.2	Applications of the Euler-Maclaurin Formula . . . . .	294

6.5 Taylor-like and Frobenius-like Series Expansions . . . . .	301
<b>7 Perturbation Theory</b>	<b>317</b>
7.1 Introduction to Perturbation Theory . . . . .	317
7.2 Regular Perturbation for Differential Equations . . . . .	326
7.3 Singular Perturbation for Differential Equations . . . . .	337
7.4 Asymptotic Matching . . . . .	352
7.4.1 Van Dyke Method . . . . .	362
7.4.2 Dealing with Logarithmic Terms . . . . .	374
7.4.3 Multiple Boundary Layers . . . . .	380
<b>8 WKBJ Theory</b>	<b>389</b>
8.1 The Exponential Approximation . . . . .	391
8.2 Region of Validity . . . . .	403
8.3 Turning Points . . . . .	417
8.3.1 One Simple Root Turning Point Problem . . . . .	426
8.3.2 Parabolic Turning Point Problems . . . . .	428
8.3.3 The Two-turning Point Schrödinger Equation . . . . .	436
<b>9 Multiple-Scale Analysis</b>	<b>443</b>
9.1 Strained Coordinates Method (Poincaré-Lindstedt) . . . . .	443
9.2 The Multiple-Scale Procedure . . . . .	457
9.3 Two-Variable Expansion Method . . . . .	465
<b>Appendix—Guide to the Special Functions</b>	<b>479</b>
<b>Answers to Odd-Numbered Problems</b>	<b>495</b>
<b>Bibliography</b>	<b>519</b>
<b>Index</b>	<b>521</b>