High Performance TCP/IP Networking

Concepts, Issues, and Solutions

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To my parents, my wife, my son Aaron, and all readers of this book

—Mahbub Hassan

To my wife, Neelu, and my sons, Sameer and Amit

—Raj Jain

Contents

Preface **xv**

1 Introduction **1**
1.1 History of TCP/IP . . . 1
1.2 TCP Applications and Services . . . 2
1.3 Motivation for Performance Study of TCP/IP . . . 3
1.4 What Do We Mean by TCP Performance? . . . 4
1.5 Overview of the Remainder of This Book . . . 6
1.6 Further Reading . . . 8
1.7 Summary . . . 9
1.8 Review Questions . . . 10
1.9 Case Study: Introduction to Wireless Corporation . . . 11

2 TCP/IP Fundamentals **12**
2.1 TCP . . . 12
2.1.1 TCP Services . . . 12
2.1.2 Header Format . . . 13
2.1.3 Encapsulation in IP . . . 16
2.1.4 Acknowledgment Mechanism . . . 16
2.1.5 Retransmission Mechanism . . . 17
2.1.6 Connection Establishment and Termination . . . 18
2.1.7 Flow Control and Sliding Window . . . 20
2.1.8 Congestion Control . . . 21
2.2 UDP . . . 23
2.2.1 UDP Services . . . 23
2.2.2 Header Format . . . 24
2.2.3 Encapsulation in IP . . . 25
2.3 IP . . . 25
2.3.1 IP Services . . . 25
2.3.2 Fragmentation and Reassembly . . . 26
2.3.3 Header Format . . . 27
2.3.4 IP Version 6 . . . 29
2.4 Further Reading . . . 29
2.5 Summary . . . 29
2.6 Review Questions . . . 29
2.7 Case Study: WCORP Adopts TCP/IP . . . 30

3 Performance Measurement of TCP/IP Networks **32**
3.1 Reasons for Network Measurement . . . 32
3.2 Measurement Tasks . . . 33
3.3 Classification of Measurement Tools . . . 33
3.4 Popular Measurement Tools and Their Applications . . . 34

3.4.1 Tcpdump . . . 35
3.4.2 Tcpstat . . . 43
3.4.3 Ttcp . . . 49
3.4.4 Netperf . . . 53
3.4.5 NetPIPE . . . 58
3.4.6 Distributed Benchmark System . . . 62
3.5 Selecting the Right Tool . . . 71
3.6 Further Reading . . . 72
3.7 Summary . . . 73
3.8 Review Questions . . . 73
3.9 Hands-on Projects . . . 74
3.10 Case Study: WCORP Monitors Network Traffic . . . 74

4 TCP/IP Network Simulation 76
4.1 The Role of Simulation . . . 76
4.2 Steps of a Systematic Simulation Study . . . 77
4.3 Types of Simulations . . . 79
4.3.1 Continuous versus Discrete Event . . . 79
4.3.2 Terminating versus Steady State . . . 80
4.3.3 Synthetic versus Trace-Driven Simulation . . . 81
4.4 Simulation Validation and Verification . . . 82
4.5 Confidence Level of Simulation Results . . . 82
4.5.1 Confidence Level Formula . . . 83
4.5.2 Terminating Simulation . . . 84
4.5.3 Steady-State Simulation . . . 84
4.5.4 Common Simulation Mistakes . . . 87
4.6 Simulation with Self-Similar Traffic . . . 88
4.7 Classification of Simulation Tools . . . 89
4.8 The ‘‘ns’’ Network Simulator . . . 90
4.8.1 Model Construction and Parameter Setting . . . 90
4.8.2 Data Collection . . . 95
4.8.3 Simulation Execution . . . 96
4.8.4 Presentation of Results . . . 97
4.8.5 Examples of TCP/IP Simulation Using *ns* . . . 97
4.9 OPNET . . . 103
4.9.1 Model Construction . . . 104
4.9.2 Parameter Setting . . . 109
4.9.3 Data Collection . . . 110
4.9.4 Simulation Execution . . . 111
4.9.5 Presentation of Results . . . 113
4.9.6 Examples of TCP/IP Simulation Using OPNET . . . 113
4.10 Selecting the Right Tool . . . 120
4.11 Further Reading . . . 121
4.12 Summary . . . 121
4.13 Review Questions . . . 122
4.14 Hands-On Projects . . . 122

4.15 Case Study: WCORP Uses Measurement, Analysis, and Simulation to Dimension Sydney–Melbourne Link Capacity 122

5 TCP Modeling 125
5.1 Motivation for Mathematical Modeling of TCP 125
5.2 Essentials of TCP Modeling 127
5.2.1 Window Dynamics 127
5.2.2 Packet-Loss Process 128
5.3 Gallery of TCP Models 128
5.3.1 Periodic Model 129
5.3.2 Detailed Packet Loss Model 131
5.3.3 Stochastic Model with General Loss Process 137
5.3.4 Control System Model 141
5.3.5 Network System Model 143
5.4 Further Reading 148
5.5 Summary 149
5.6 Review Questions 150
5.7 Hands-on Projects 151
5.8 Case Study: Understanding Factors Influencing TCP Throughput . 151

6 TCP/IP Performance over Wireless Networks 153
6.1 Wireless Networks 153
6.1.1 Generic Characteristics 153
6.1.2 Wireless Local Area Networks 154
6.1.3 Cellular Communications Networks 156
6.2 TCP Performance Issues over Wireless Links 157
6.2.1 Inappropriate Reduction of Congestion Window 157
6.2.2 Throughput Loss in WLANs 158
6.2.3 Throughput Loss in Cellular Communication Systems . . . 159
6.3 Improving TCP Performance over Wireless Links 161
6.3.1 Splitting TCP Connections 161
6.3.2 Snooping TCP at Base Stations 161
6.3.3 Notifying the Causes of Packet Loss 162
6.3.4 Adding Selective Acknowledgments to TCP 163
6.3.5 Summary and Comparison of Enhancement Schemes . . . 163
6.4 Wireless System Evolution and TCP/IP 164
6.4.1 Trends in Cellular Communication Systems 164
6.4.2 Trends in Wireless LAN Systems 165
6.4.3 TCP/IP over Heterogeneous Wireless Systems 165
6.5 Further Reading 166
6.6 Summary 167
6.7 Review Questions 167
6.8 Hands-On Projects 168
6.9 Case Study: WCORP Installs Wireless LANs 168

7 TCP/IP Performance over Mobile Networks 170
7.1 Cellular and Ad Hoc Networks 170
7.2 TCP Performance in Cellular Networks 171

7.2.1 Mobile IP . . . 171
7.2.2 Impact of Mobility on TCP Performance . . . 173
7.2.3 Approaches to Improve TCP Performance . . . 174
7.3 TCP Performance in Ad Hoc Networks . . . 177
7.3.1 Dynamic Source Routing . . . 178
7.3.2 Impact of Mobility on TCP Performance . . . 178
7.3.3 Approaches to Improve TCP Performance . . . 179
7.4 Further Reading . . . 181
7.5 Summary . . . 182
7.6 Review Questions . . . 182
7.7 Hands-On Projects . . . 183
7.8 Case Study: WCORP Tunes TCP to Combat Blackouts in Mobile Networking . . . 183

8 TCP/IP Performance over Optical Networks 185
8.1 Evolution of Optical Networks . . . 185
8.2 IP over DWDM . . . 186
8.3 Multiprotocol Label Switching . . . 188
8.4 Multiprotocol Lambda Switching . . . 189
8.5 Optical Burst Switching . . . 190
8.6 Optical Packet Switching . . . 192
8.6.1 Optical Packet Format . . . 193
8.6.2 Congestion Resolution in Optical Packet Switches . . . 195
8.7 Performance of TCP/IP over Optical Networks . . . 197
8.7.1 Optical Packet Network End-to-End Performance . . . 198
8.7.2 Mapping of TCP in Optical Packets . . . 199
8.7.3 Optical Packet Design in the TCP/IP Environment . . . 201
8.8 Further Reading . . . 204
8.9 Summary . . . 204
8.10 Review Questions . . . 204
8.11 Hands-On Projects . . . 205

9 TCP/IP Performance over Satellite Networks 206
9.1 A Brief History of Data Satellites . . . 206
9.2 Motivations for Using Satellites . . . 207
9.3 Types of Satellites . . . 208
9.4 Satellite Internet Architectures . . . 209
9.5 Satellite Characteristics Affecting TCP . . . 211
9.5.1 Long Feedback Loop . . . 211
9.5.2 Link Impairment . . . 214
9.5.3 Bandwidth-Delay Product . . . 215
9.5.4 Bandwidth Asymmetry . . . 216
9.5.5 Variable Delays . . . 217
9.5.6 LEO Handoff . . . 217
9.5.7 Spectral Congestion . . . 217
9.5.8 Security . . . 217

9.6 Goals for TCP Performance Enhancement Solutions 217
9.7 TCP Enhancements for Satellite Networks 219
9.7.1 Path MTU Discovery 219
9.7.2 TCP for Transactions 219
9.7.3 Window Scaling 220
9.7.4 Large Initial Window 221
9.7.5 Byte Counting 223
9.7.6 Delayed ACKs after Slow Start 224
9.7.7 Explicit Congestion Notification 225
9.7.8 Multiple Connections 225
9.7.9 Pacing TCP Segments 226
9.7.10 TCP/IP Header Compression 226
9.7.11 Security Issues 227
9.7.12 Conclusions for TCP Enhancements 228
9.8 Advanced Enhancements and New Versions of TCP 229
9.8.1 Quick-Start TCP 229
9.8.2 HighSpeed TCP 230
9.8.3 TCP Peach 230
9.8.4 Explicit Transport Error Notification 231
9.8.5 TCP Westwood 231
9.8.6 XCP 231
9.9 New Transport Protocols for Satellite Links 232
9.9.1 Satellite Transport Protocol 232
9.9.2 Space Communications Protocol Specifications-Transport Protocol 233
9.10 Performance Enhancing Proxy 233
9.10.1 Motivations for the Use of PEP on Satellite Networks . . . 233
9.10.2 Types of Performance Enhancing Proxies 234
9.10.3 Mechanisms Used in Performance Enhancing Proxies . . . 236
9.10.4 Implications of Using Performance Enhancing Proxies . . . 237
9.10.5 Security with Performance Enhancing Proxies 238
9.10.6 Commercial PEP (SkyX) 239
9.11 Further Reading 240
9.12 Summary 241
9.13 Review Questions 242
9.14 Hands-On Projects 243
9.15 Case Study: Improving TCP Performance over Satellite Using SkyX 243

10 TCP/IP Performance over Asymmetric Networks 247
10.1 Types of Network Asymmetry 248
10.1.1 Bandwidth Asymmetry 248
10.1.2 Media-Access Asymmetry 249
10.1.3 Loss Rate Asymmetry 249
10.2 Impact of Asymmetry on TCP Performance 249
10.2.1 Bandwidth Asymmetry 249
10.2.2 Media-Access Asymmetry 251
10.3 Improving TCP Performance over Asymmetric Networks 255

10.3.1 Uplink Bandwidth Management . . . 255
10.3.2 Handling Infrequent ACKs . . . 257
10.4 Experimental Evaluation of Performance Improvement Techniques 259
10.4.1 Experiments with Bandwidth Asymmetry . . . 259
10.4.2 Experiments with Media-Access Asymmetry . . . 260
10.5 Further Reading . . . 260
10.6 Summary . . . 262
10.7 Review Questions . . . 262
10.8 Hands-On Projects . . . 262
10.9 Case Study: Improving TCP Performance over ADSL . . . 262

11 New TCP Standards and Flavors 264
11.1 Duplicate Acknowledgments and Fast Retransmit . . . 264
11.2 Fast Recovery and TCP Reno . . . 265
11.3 TCP NewReno . . . 266
11.4 TCP with Selective Acknowledgments . . . 267
11.5 Forward Acknowledgments . . . 268
11.6 TCP Vegas . . . 268
11.7 Overview of Other Features and Options . . . 269
11.8 Performance Comparison of TCP Flavors . . . 270
11.9 Further Reading . . . 278
11.10 Summary . . . 278
11.11 Review Questions . . . 278
11.12 Hands-On Projects . . . 278
11.13 Case Study: High Performance TCP for Computational Grid . . . 279

12 Active Queue Management in TCP/IP Networks 281
12.1 Passive Queue Management . . . 281
12.1.1 Tail-Drop . . . 282
12.1.2 Drop-From-Front . . . 282
12.1.3 Push-Out . . . 283
12.1.4 Problems with Passive Queue Management . . . 283
12.2 Active Queue Management . . . 284
12.2.1 Random Early Detection . . . 284
12.2.2 Classifying the RED Variants . . . 287
12.2.3 RED Variants with Aggregate Control . . . 288
12.2.4 RED Variants with Per-Flow Accounting . . . 294
12.3 Performance Evaluation and Comparison of AQM Schemes . . . 299
12.3.1 Throughput and Fairness . . . 299
12.3.2 Delay and Jitter . . . 301
12.3.3 Time Response . . . 301
12.3.4 Traffic Oscillation . . . 302
12.3.5 Performance Summary of AQM Schemes . . . 302
12.4 AQM and Differentiated Service . . . 302
12.5 Further Reading . . . 304
12.6 Summary . . . 305
12.7 Review Questions . . . 306

12.8 Hands-On Project . . . 306
12.9 Case Study: WCORP Deploys Active Queue Management . . . 307

13 TCP Implementation 308
13.1 TCP Implementation Overview . . . 309
13.1.1 Buffering and Data Movement . . . 311
13.1.2 Accessing User Memory . . . 311
13.1.3 TCP Data Exchange . . . 313
13.1.4 Retransmissions . . . 316
13.1.5 Congestion . . . 316
13.2 High Performance TCP . . . 317
13.2.1 High-Bandwidth-Delay Products . . . 317
13.2.2 Round-Trip Estimation . . . 318
13.2.3 Path MTU Discovery . . . 318
13.3 Reducing End-System Overhead . . . 319
13.3.1 Overhead, CPU Utilization, and Bandwidth . . . 320
13.3.2 The Role of Application Processing . . . 321
13.3.3 Sources of Overhead for TCP/IP . . . 322
13.3.4 Per-Packet Overhead . . . 323
13.3.5 Interrupts . . . 324
13.3.6 Checksums . . . 325
13.3.7 Connection Management . . . 326
13.4 Copy Avoidance . . . 326
13.4.1 Page Remapping . . . 327
13.4.2 Scatter/Gather I/O . . . 329
13.4.3 Remote Direct Memory Access . . . 330
13.5 TCP Offload . . . 331
13.6 Further Reading . . . 333
13.7 Summary . . . 333
13.8 Review Questions . . . 333
13.9 Hands-On Projects . . . 334

A M/M/1 Queues 335

B FreeBSD 338
B.1 Installation . . . 338
B.2 Configuration . . . 338
B.2.1 Network Card Configuration . . . 338
B.2.2 Starting Network Services . . . 339
B.3 Kernel Modification . . . 339
B.3.1 Modify Kernel Configuration Files . . . 339
B.3.2 Modify Kernel Source Files . . . 340
B.3.3 Build and Install the New Kernel . . . 341
B.3.4 Kernel Error Recovery Technique . . . 341
B.3.5 Kernel Modification Example . . . 342

C TCP Auto-Tuning 345
C.1 Motivation for TCP Auto-Tuning . . . 345

C.2 TCP Auto-Tuning Techniques and Products 345
C.3 Selecting Auto-Tuned TCP 346
C.4 Further Reading 347

Bibliography **348**

Index **367**

Preface

The world is undergoing a revolution in information and communication technology. Not only the lives of citizens but also the networking technology are profoundly affected by this revolution. Traditional wired networks are being replaced or complemented by networks based on wireless, optical, satellite, and other media. TCP/IP has emerged as the global Internet-working solution allowing communication over a wide variety of media and networks. These new networking media and the new ways of communication over these networks have given rise to a host of new performance issues and concepts. To adapt and contribute effectively to such changes, engineers and computer scientists must acquire a solid foundation and understanding of the fundamental concepts that affect performance in TCP/IP networks.

Existing texts on TCP/IP focus on the presentation of the protocol details with little coverage of the performance issues and concepts. These texts are good for a first course on TCP/IP networking but do not provide sufficient material for those advanced readers interested in acquiring in-depth knowledge of the performance aspects of TCP/IP, especially in the emerging networking environment. To address this need, we have written *High Performance TCP/IP Networking: Concepts, Issues, and Solutions*, with a clear focus on the performance fundamentals of TCP/IP.

High Performance TCP/IP Networking: Concepts, Issues, and Solutions is a comprehensive guide to the study of its topic. Our book provides an in-depth coverage of (1) tools and techniques for the performance evaluation of TCP/IP networks, (2) performance concepts and issues for running TCP/IP over wireless, mobile, optical, and satellite networks, (3) congestion-control algorithms in hosts and routers, and (4) high performance implementation of TCP/IP protocol stack. This text has been created with an emphasis on fundamental concepts, such as network measurement and simulation techniques, mathematical modeling of TCP dynamics, and management of implementation overhead, which will continue to guide new developments in TCP/IP. Although many specific networks, tools, and protocols are discussed in the text, a continuous effort has been made to emphasize the underlying performance issues and concepts.

CONTRIBUTING AUTHORS

This book contains contributions from many leading experts actively working on specific performance issues in TCP/IP networks. In addition to the two editors (Hassan and Jain), who themselves wrote parts of the book, there are a total of 24 authors who wrote specific chapters of the book. One of the most challenging tasks was to integrate these individual submissions into a coherent book. As part of the integration effort, the editors have introduced a range of additional materials, including learning objectives, review questions, hands-on projects, and case studies. The editors maintained close liaison with the chapter authors throughout the manuscript preparation process. The manuscript was reviewed and revised twice to address the concerns of the reviewers. Substantial material was added in each revision to further integrate the chapters and improve the quality of the book. While most individual chapter authors were contacted for the revisions, the editors

themselves revised some of the chapters. The list of authors who contributed to this book follows (chapters that were substantially revised by the editors are marked with an asterisk).

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ORGANIZATION AND OUTLINE

The book is organized into five parts.

- **Part I: Background.** Part I provides an introduction to the book. It contains two chapters. Chapter 1 provides a rationale for the book. Chapter 2 reviews some of the key features of TCP/IP protocols used in later chapters in the book to explain many performance issues. Chapter 2 reviews only the key features of TCP/IP. A comprehensive treatment of TCP/IP protocol stack is beyond the scope of the book.

- **Part II: Performance Evaluation.** Part II consists of Chapters 3, 4, and 5 and provides detailed coverage of the tools and techniques for performance evaluation of TCP/IP networks. Chapter 3 discusses the performance measurement tools available for monitoring, analyzing, and benchmarking the performance of TCP/IP networks. Chapter 4 introduces simulation techniques and discusses two popular simulation tools. Chapter 5 is devoted to the mathematical modeling of TCP congestion control algorithms.

- **Part III: Performance in Emerging Networks.** Chapters 6 through 10 examine the performance concepts and issues for running TCP/IP in the emerging networking environment. Although many of us think modems and Ethernet when we think Internet and TCP/IP, this is no longer the reality. Yes, it is true that nearly every home has a modem for Internet connection, and nearly every organization has some version of the wired Ethernet connectivity to the desktop. Many homes, however, are subscribing to Digital Subscriber Loop (DSL) technologies for high-speed Internet connection, and many organizations are deploying wireless LANs for flexibility. In the wide area, too, we are witnessing new networking technologies such as mobile cellular data networks (e.g., GPRS), high-speed optical backbones, and increasing use of satellite links for long-distance and global coverage. Each of these new technologies has given rise to some new concepts and issues for TCP/IP performance. We have therefore dedicated a separate chapter to deal with each of these technologies: Chapter 6 for wireless, Chapter 7 for mobility, Chapter 8 for optical, Chapter 9 for satellite, and Chapter 10 for asymmetric networks (e.g., ADSL).

- **Part IV: Congestion Control.** With the increase in networking complexities and traffic dynamics, congestion-control algorithms employed at the end hosts and in the network routers continue to evolve. The new congestion-control algorithms in the TCP protocol resulted in many different TCP flavors (e.g.,

Tahoe, Reno, Vegas, and so on). Part IV consists of Chapters 11 and 12 and presents an in-depth coverage of the congestion-control algorithms proposed so far. Chapter 11 discusses various TCP flavors, and Chapter 12 examines the new queue management schemes proposed for the network routers to combat congestion in highly dynamic environment.

- **Part V: Implementation.** For emerging high-speed networks (e.g., 10 Gbps Ethernet), the end-system implementation of TCP can become a performance bottleneck. Part V (Chapter 13) summarizes critical performance issues for TCP implementation in end systems and surveys solutions for improving bulk transfer performance.

HOW TO USE THIS BOOK

The book is designed for use in a second course on networking with a prerequisite course on introductory networking or data communications. Some of the possible courses for which this book can be used include Advanced Computer Networks, Advanced TCP/IP Networks, High Performance Networks, and Internet-working. There is enough material in the book for a one-semester or one-quarter course with 12 or 13 weeks of lecture. Depending on the background of the students, two possible course compositions are given here.

Computer science students with limited background in mathematics and hardware design can exclude Chapter 5 (mathematical modeling) and study Chapter 4 (Simulation) in more detail. Engineering students graduating in computer or electrical engineering can spend fewer weeks on Chapter 4 and one extra week on Chapter 5.

Professionals working as network engineers, R & D managers, research scientists, and network administrators will also find this book valuable as a reference to the most recent advances in TCP performance research.

LEARNING AIDS

There are many learning aids in this book:

- **Learning Objectives.** Each chapter starts with a list of learning objectives. The learning objectives highlight the fundamental concepts (skills) students should understand (master) as a result of reading the chapter and help them organize their study goals. They assist instructors in pointing out lecture objectives.

- **Further Reading Lists.** Annotated reading lists at the end of the chapters provide students with valuable resources for independent exploration on specific topics of interest. These lists are particularly useful for professionals.

- **Chapter Summaries.** Summaries offer students a chance to review their understanding of key concepts in the chapter before moving on.

- **Review Questions.** End-of-chapter review questions evaluate the degree to which the student achieved the learning objectives and force the students to think about the key concepts in the chapter. Answers to most of the review questions can be found directly from the chapter; therefore, students are

forced to reread parts of the chapter to locate the answers. Such rereading is often required to gain a clear understanding of many difficult concepts. The instructor can use some of these questions for classroom discussions or class tests.

- **Hands-On Projects.** For each chapter, a list of performance evaluation experiments are provided for advanced students seeking to gain a deeper understanding of some of the key concepts and solutions described in the chapter. These experiments can be carried out on open platforms using freely available software. The hands-on projects in this book cover a range of difficulty. Some experiments can be completed in a few weeks using *ns*-2 simulation software, without requiring any kernel-level programming. Other experiments require modification of existing TCP/IP stacks in FreeBSD operating system kernel. These experiments are quite challenging and can be given to students as whole semester projects. Students attempting these experiments are expected to have a good background in programming and operating systems. (Appendix B provides a brief tutorial on FreeBSD for students with no prior background in kernel programming.)

- **Case Studies.** A case study is introduced in Chapter 1 based on a fictitious, but realistic organization with TCP/IP networking infrastructure. The same case study is then used in subsequent chapters with some modifications to introduce new performance problems. The running case study holds together different chapters in the text, provides students a realistic context in which to apply the concepts and techniques learned in the relevant chapters, and yields a classroom discussion topic for the instructor.

- **Figures and Illustrations.** Many concepts throughout the book are explained using illustrations. These illustrations help students understand complex performance issues and concepts.

- **Examples.** Examples have been used where applicable to explain the use of techniques learned from the text.

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The book would never exist without the contributions from the individual chapter authors. We take this opportunity to thank all chapter authors for their expertise and time and for putting up with our many requests throughout the preparation of the manuscript. We are indebted to the anonymous reviewers for reading the whole manuscript or part of the earlier versions of the manuscript and making useful comments. Their constructive suggestions significantly influenced the revisions of the manuscript. We thank Professor Krzysztof Pawlikowski of the University of Canterbury, New Zealand, for providing early feedback on Chapter 4. The author of Chapter 11 thanks Tapan Karwa, Venkatesh Prabhakar, Farnaz Erfan, and Minseok Kwon for their help with the simulation experiments in that chapter. Jim Wu, a coauthor of Chapter 4, has been instrumental in fixing some of the problems we faced in preparing the manuscript in LaTex. We gratefully acknowledge the support of the entire production team at Prentice Hall. Finally, the first editor (Hassan)

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