# Contents

List of Excursions ix

Preface xi

0.1 Background of This Book xi

0.2 Acknowledgments xi

1 Introduction 1

1.1 Focus of This Book 1

1.2 Structure of This Book 3

1.3 Classification of Bugs 3

2 Machine Numbers, Precision, and Rounding Errors 9

2.1 The Failure of the Ariane 5 10

2.2 Y2K and Data Formats 26

2.3 Vancouver Stock Exchange 30

2.4 The Patriot Missile Defense Incident 40

3 Mathematical Modeling and Discretization 51

3.1 Loss of the Gas Rig Sleipner A 52

3.2 London Millennium Bridge 75

3.3 Weather Prediction 79

3.4 Mathematical Finance 93

4 Design of Control Systems 103

4.1 Fly-by-Wire 103

4.2 Automotive Bugs 114

5 Synchronization and Scheduling 125

5.1 Space Shuttle 125

5.2 Mars Pathfinder 134

6 Software-Hardware Interplay 145

6.1 The Pentium Division Bug 145

6.2 Mars Rover Spirit Flash Memory Problem 164

7 Complexity 171

7.1 Therac-25 171

7.2 Denver Airport 192

7.3 Strategic Defense Initiative 213
8 Appendix

8.1 Urban Legends and Other Stories .............................................. 219
8.2 MATLAB Example Programs ...................................................... 227
8.3 Pentium Bug: Original Email of T. Nicely to Several Individuals and Groups .......................................................... 240

Index ......................................................................................... 247
Preface

0.1 Background of This Book

The interest in numerical bugs originated from a post by Pete Stewart in the October 1999 edition of NA Digest\(^1\) (see [1]). There, Pete Stewart mentioned interesting numerical bugs and challenged readers to provide further examples. The first list of examples comprised the Patriot failure, the explosion of Ariane 5, index computation of the Vancouver Stock Exchange, and the Green Party rounding error in parliamentary elections in Germany. Later on, Stewart’s collection grew (and was summarized on different websites), adding the sinking of the Sleipner gas rig, the Denver Airport baggage-handling disaster, the Pentium division bug, the Y2K problem, and the loss of the Mars Climate Orbiter. Over the years, the number of numerical bugs kept growing and attracted a lot of interest.

In particular, one of the authors closely followed this interesting development. In about 2000, he started to collect corresponding material on a website\(^2\) and worked on the topics in seminars and presentations. It turned out that the cases get more complex and sometimes also inconsistent the deeper one dives into the topics and related literature. Typically, a lot of material exists in the literature on all of the cases. Sometimes, surveys are nicely compact but simplify the real reasons (considerably). Frequently, only certain aspects were in the focus of the corresponding authors. Therefore, it pays off to bring together all the relevant material of the selected bugs in one place in a thorough scientific manner.

0.2 Acknowledgments

Many people supported us with respect to proofreading specific sections. In alphabetical order, we thank Long Chen, Alan Edelman, Michael Grad, Svenja Huckle, Florian Jarre, Julius Knorr, Anja Neckel, Alois Pichler, Alexander Pöppl, Roland Potthast, Karl-Heinz Reineck, Christoph Riesinger, Florian Rupp, Alexander Sauter, Ultich Schättler, Stephen Seckler, Robert Skeel, Carsten Uphoff, Korad Waldherr, and Roland Wittmann.

Concerning valuable hints to certain interesting software bugs, special thanks go to Andreas Blüml, Bernd Brügge, Oliver Ernst, William Kahan, Daniel Kressner, Helmut Seidl, and Pete Stewart.

For useful discussion and information on certain bugs, we thank Kevlin Henney (Ariane), Berit Alstad, Norb DeLatte, Kevin Parfitt, Karl-Heinz Reineck, Keith Thompson, Ger Wackers (Sleipner), Long Chen (Millennium Bridge), Andreas Fink, Detlev Majewski, Joaquim Pinto, Florian Prill, Ulrich Schättler, Uwe Ulbrich (weather fore...

---

\(^1\)“The NA Digest is a collection of articles on topics related to numerical analysis and those who practice it” (see [http://www.netlib.org/na-digest-html/](http://www.netlib.org/na-digest-html/)). It also offers a weekly email newsletter.

\(^2\)[https://www5.in.tum.de/persons/huckle/bugse.html](https://www5.in.tum.de/persons/huckle/bugse.html)
cast), William Kahan, Christoph Lauter, Tobias Nipkow, Christoph Riesinger, Florian Schnagl (Pentium), Leo Eichhorn (Mars Rover flash memory), Gunter Artl, Florian Jarre (Denver and Heathrow Airports), Manfred Broy, and Michael Grad (automotive).

Furthermore, we thank SIAM and, in particular, Elizabeth Greenspan and Gina Rinelli Harris for all the constructive feedback and support. And last but not least, we gratefully acknowledge the comments and propositions of all reviewers, which considerably contributed to improving the quality of this book.

**Bibliography**

Index

Abbey Hill Equipment, 45
accuracy, 33, 35, 43 58 62 69
70 81 83 85 109, 153.
155, 157, 207
Ada, 15, 17
ADIRU, see Air Data Inertial
Reference Unit
Advanced Field Artillery
Tactical Data System, 88
AECL, see Atomic Energy of
Canada Limited
Aegis, 40 89 214
aerospace, 27, 135
AHE, see Abbey Hill Equipment
aileron, 108
Air Canada, 22
Air Data Inertial Reference
Unit, 109
Air France, 109
air traffic controller, 110
air transportation, 28
airbag, 100, 114-116, 135
Airbus, 89, 104-108, 110, 111
Airbus A400M Atlas, 108
Al Hussein, see also Scud, 41
42 44
algorithmic trading, see also
algotrading, 94
algotrading, see algorithmic
trading
Alstec, 206
AMD, 145, 161
Angular momentum
desaturation, 21
Apple Macintosh, 29
Ariane, xi 3 9-11, 15-18 21
128
Arianespace, 10
ASCII, 12
ASI/MET, see Atmospheric
Structure Instrument/
Meteorologic Package
aspect ratio, 57. 58. 66. 70. 72
ATC, see air traffic controller
ATM card, 28
Atmospheric Structure
Instrument/Meteorologic
Package, see also
ASI/MET, 135, 136,
138-141
Atomic Energy of Canada
Limited, 172, 177-179.
185
Austerlitz, 219
automotive, 27, 114 115
autonomous driving, 115, 116.
118 188
Autopilot, 109 110. 117-119
BA, see British Airways
BAA, see British Airport
Authority
babies, 28
Backup Flight control System,
128 131
BAE Automated Systems, 193
194 203-206
baggage-handling system, see
also BHS, 192. 194 195.
203 205 206
Baikonur, 11, 89, 90
Ballistic Missile Early Warning
System, 223
bank account number, 22
Bank of America, 219
Bank of New York, 220
BART, see Bay Area Rapid
Transit
basis function, 57
Bay Area Rapid Transit, 222
Bayesian Data Assimilation, 85
Beagle 2, 141
BFS, see Backup Flight control
System
BHS, see also baggage-handling
system, 192-194, 197
199 203 205, 206
Bitcoin, 18
Black Monday, 94
black swan, 68, 99 100
Black–Scholes, 56 96, 99
blood analysis device, 190
BMEMS, see Ballistic Missile
Early Warning System
BMW, 120
BNP, see Neidle Patrone
Associates
Boeing, 22 104, 105 111, 126.
127
boundary conditions, 78 85 86
Brilliant Pebbles, 214
British Airport Authority, 206
208
British Airways, 206-208
Brownian motion, 96
Broy, M., 116
butterfly effect, 83
CAD, 111
calculator, 37
camera, 103. 117 135. 221
cancellation, 81
carry ahead, 146 147
carry-save, 146. 147 153. 154
157. 158
cast, 14-17
CCP, see cyclic counter process
CDO, see collateralized debt
obligations
CDS, see credit default swaps
Celsius, 38
Central processing unit, 130
146. 160 164

247
general purpose computer, 128–131
German Railway, 168
Giotto, 10
Gisborne Hospital, 189
global model, 83 85–87
Global Protection Against
Limited Strikes, 214
GMD, see Ground-based
Midcourse Defense
GME, see global model
Google, 116
GPALS, see Global Protection
Against Limited Strikes
GME, see global model
GPS, 29, 89, 110, 142
gravity-based structure, 52, 62
Green Party, xi, 36
Gregorian calendar, 219
Grigg–Skjellerup, 10
Gripen, 222
ground mode, 108
Ground-based Midcourse
Defense, 214
Hadoop, 28
Halley, 10
heart monitor, 28
Heisenberg effect, 5, 228
HELIXORTER, 207
High Precision Tracking
Experiment, 216
HMS Sheffield, 45
HOE, see Homing Overlay
Experiment
Homing Overlay Experiment, 216
hot run, 223
HPTE, see High Precision
Tracking Experiment
human-computer interaction, 107
Hypermelodically Railgun, 214
i486, 151, 153
IBM, 29, 128, 129, 135 151.
159, 161, 206
ICON model, 84
Identification Friendly or Foe, 89
IEEE, 4, 14, 21, 37
IFF, see Identification Friendly
or Foe
ill-conditioned, 80–83, 86, 98
infusion pump, 190
initial values, 3 84, 86 180
input data, 3 33 51. 184 216.
220
integer overflow, 10 13 172.
188
Intelsat 603, 22
International Space Station, 126.
141
International Y2K Cooperation
Center, 27
Internet, 94 151 161
interpolation, 55 57–60, 84
interprocess communication
mechanism, 139
IPC, see interprocess
communication
mechanism
ISS, see International Space
Station
Java, 28
Jean Monnet Hospital, 189
Jet Propulsion Laboratory, 21.
135–137, 140 165. 168
JPL, see Jet Propulsion
Laboratory
Julian calendar, 219
Kahan, W., 152, 159, 160
Kaiser, A., 151
Kennestone Regional Oncology
Center, 173
Knight Capital Group, 95
Kosmos satellite, 224
Kuala Lumpur International
Airport, 208
Lagrange polynomial, 59
Laspeyres index, 31
Lauda Air, 104
Laufenburg, 221
LB, see line balancing
leap second bug, 28
leap year bug, 29
legacy software, 26, 27
line balancing, 197 199, 205
line of rails, 221
LinkedIn, 28
Linux kernel 3.6, 171
LM, see local model
local model, 83–86
Lockheed Martin, 135. 216
logistic parabola, 82
Logplan, 194
London Heathrow Terminal 5,
204. 206–208
London Millennium Bridge, 51.
76 77
London Underground, 222
lookup table, 145 152.
154–158 160
Lothar, 51, 79 80 84, 86, 87
Lufthansa, 105
Mac OS X 10.4, 171
machine number, 2 12–15 32
37 42 43. 153–155
Mallorca, 88
mantis, 13 14 32, 42 146
148, 152 159
Mariner, 134
Mariner 1, 224
Mars Climate Orbiter, xi 21
Mars Exploration Rover, 164
166, 167
Mars Global Surveyor, 164 226
Mars Pathfinder, 125 134
Mars Polar Landers, 141
Mars rover Opportunity, 164.
168
Mars rover Sojourner, 135–137
139
Mars rover Spirit, 145 164–168
MasterNet, 219
MATLAB, 2, 3, 5, 33–35, 37.
38 56 59, 80, 152, 155.
227
MCO, see Mars Climate Orbiter
MER, see Mars Exploration
Rover
Meteo France, 28
Meteor-M satellite, 90
Microsoft, 36, 37, 166
Millennium Bug, see Y2K bug
Mobileye, 117
modern portfolio theory, 97 98
Moler, C., 152
monitoring device, 190
Motorola, 15
Mozilla, 28
MPL, see Mars Polar Landers
MPT, see modern portfolio
theory
MSC/NASTRAN, 63, 67, 69, 70
Multimedia Systems
International, 189
mutex, see mutual exclusion
mutual exclusion, 137–140
<table>
<thead>
<tr>
<th>Index</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Titan Centaur, 88</td>
<td></td>
</tr>
<tr>
<td>Tornado, 45</td>
<td></td>
</tr>
<tr>
<td>torpedo, 223</td>
<td></td>
</tr>
<tr>
<td>Toyota, 120</td>
<td></td>
</tr>
<tr>
<td>Prius, 120</td>
<td></td>
</tr>
<tr>
<td>Traffic Collision Avoiding System, 109, 110</td>
<td></td>
</tr>
<tr>
<td>traveling salesman problem, 199</td>
<td></td>
</tr>
<tr>
<td>tricell, 61-65 67-72</td>
<td></td>
</tr>
<tr>
<td>two’s complement, 146 148</td>
<td>156</td>
</tr>
<tr>
<td>UA, see United Airlines</td>
<td></td>
</tr>
<tr>
<td>Überlingen, 109</td>
<td></td>
</tr>
<tr>
<td>United Airlines, 193, 194 204</td>
<td></td>
</tr>
<tr>
<td>UNIX, 29</td>
<td></td>
</tr>
<tr>
<td>Uranus, 225</td>
<td></td>
</tr>
<tr>
<td>US F-16, 222</td>
<td></td>
</tr>
<tr>
<td>US Hornet, 45</td>
<td></td>
</tr>
<tr>
<td>US National Weather Service, 87</td>
<td></td>
</tr>
<tr>
<td>US Naval Observatory, 28</td>
<td></td>
</tr>
<tr>
<td>US spy satellites, 28</td>
<td></td>
</tr>
<tr>
<td>USS Scorpion, 223</td>
<td></td>
</tr>
<tr>
<td>USS Squalus, 223</td>
<td></td>
</tr>
<tr>
<td>USS Tang, 223</td>
<td></td>
</tr>
<tr>
<td>USS Tullibee, 223</td>
<td></td>
</tr>
<tr>
<td>USS Vincennes, 89</td>
<td></td>
</tr>
<tr>
<td>USS Yorktown, 88</td>
<td></td>
</tr>
<tr>
<td>validation, 2</td>
<td></td>
</tr>
<tr>
<td>Value at Risk, 97 98</td>
<td></td>
</tr>
<tr>
<td>Vancouver Stock Exchange, xi</td>
<td>31</td>
</tr>
<tr>
<td>33-36</td>
<td></td>
</tr>
<tr>
<td>Vanderlande Industries, 206</td>
<td></td>
</tr>
<tr>
<td>VaR, see Value at Risk</td>
<td></td>
</tr>
<tr>
<td>verification, 2</td>
<td></td>
</tr>
<tr>
<td>Veritec, 70</td>
<td></td>
</tr>
<tr>
<td>Viking, 134</td>
<td></td>
</tr>
<tr>
<td>Volkswagen, 115 116</td>
<td></td>
</tr>
<tr>
<td>Vostochny, 89</td>
<td></td>
</tr>
<tr>
<td>Voyager, 225</td>
<td></td>
</tr>
<tr>
<td>VSE, see Vancouver Stock Exchange</td>
<td></td>
</tr>
<tr>
<td>VxWorks, 135 166</td>
<td></td>
</tr>
<tr>
<td>Warszawa, 105</td>
<td></td>
</tr>
<tr>
<td>Warsaw Pact, 213</td>
<td></td>
</tr>
<tr>
<td>WCC, see weapons control computer</td>
<td></td>
</tr>
<tr>
<td>Weapons control computer, 40</td>
<td></td>
</tr>
<tr>
<td>weather prediction, 56, 80 87 99</td>
<td></td>
</tr>
<tr>
<td>weather service, 80 86</td>
<td></td>
</tr>
<tr>
<td>Windows XP, 171</td>
<td></td>
</tr>
<tr>
<td>WindRiver, 135</td>
<td></td>
</tr>
<tr>
<td>X-band radar, 214</td>
<td></td>
</tr>
<tr>
<td>X-ray application, 172</td>
<td></td>
</tr>
<tr>
<td>Xerox, 89</td>
<td></td>
</tr>
<tr>
<td>Y2K bug, xi 26-28</td>
<td></td>
</tr>
<tr>
<td>Y2K+10, 29</td>
<td></td>
</tr>
<tr>
<td>Yakima Valley Memorial Hospital, 173</td>
<td></td>
</tr>
<tr>
<td>Year 2000 Bug, see Y2K bug</td>
<td></td>
</tr>
<tr>
<td>Zenobia, 222</td>
<td></td>
</tr>
</tbody>
</table>