



*the finest machine*  
the science and the joy of computing

---

nick black

DEDICATED to my professors, my students, and my friends at the Georgia Institute of Technology, who give rise to that spirit living *in his machinis ex deis*. Hack on, lads, hack on!

TO ALL THOSE who took a wary chance on a risky bet, especially Coach Jeanette Martin: thanks for everything. You made possible this work of tightly-controlled audacity. *Per ardua ad astra*.

–Atlanta, 2011

I made a discovery today. I found a computer... And then it happened... a door opened to a world... rushing through the phone line like heroin through an addict's veins, an electronic pulse is sent out, a refuge from the day-to-day... This is it, this is where I belong.

—The Mentor, “The Hacker Manifesto”  
*Phrack* Vol. One, Issue Seven, Phile 3 (1986-09-25)

Something else gets under your skin, keeps you working days and nights at the sacrifice of your sleeping and eating and attention to your family and friends, something beyond the love of puzzle solving. And that other force is the anticipation of understanding something about the world that no one has ever understood before you... I have experienced that pleasure of discovering something new. It is an exquisite sensation, a feeling of power, a rush of the blood, a sense of living forever. To be the first vessel to hold this new thing.

All of the scientists I've known have at least one more quality in common: they do what they do because they love it, and because they cannot imagine doing anything else. In a sense, this is the real reason a scientist does science. Because the scientist must. Such a compulsion is both blessing and burden. A blessing because the creative life, in any endeavor, is a gift filled with beauty and not given to everyone, a burden because the call is unrelenting and can drown out the rest of life.

This mixed blessing and burden must be why the astrophysicist Chandrasekhar continued working until his mid-80's, why a visitor to Einstein's apartment in Bern found the young physicist rocking his infant with one hand while doing mathematical calculations with the other. This mixed blessing and burden must have been the “sweet hell” that Walt Whitman referred to when he realized at a young age that he was destined to be a poet. “Never more,” he wrote, “shall I escape.”

—Alan Lightman, “Spellbound by the Eternal Riddle, Scientists Revel in Their Captivity”,  
New York Times (2003-11-11)

Part of the inhumanity of the computer is that, once it is competently programmed and working smoothly, it is completely honest. I do not fear computers. I fear the lack of them.

—Isaac Asimov, source unknown

Nature does not know extinction; all it knows is transformation. Everything science has taught me, and continues to teach me, strengthens my belief in the continuity of our spiritual existence.

—Wernher Von Braun, “Why I Believe in Immortality”,  
from *The Third Book of Words to Live By*, W. Nichols (ed.) (1962)

In the particular is contained the universal.

—Anton Chekhov, as quoted by James Joyce in  
Arthur Power's *From the Old Waterford House* (1949)

There may indeed be other applications of the system than its use as a logic.

—Alonzo Church,  
*The Calculi of Lambda-Conversion* (1932)

# Contents

0.1	DEDICATION . . . . .	2
0.2	PREFACE . . . . .	4
0.3	INTRODUCTION: For madmen only. Price of admission: your mind. . . . .	4
	<b>Contents</b>	<b>4</b>
	<b>I BEYOND THE ZERO.</b>	<b>7</b>
1	Countable and uncountable numbers. Diagonalization. Gödel numbering and semiotics. Formally undecidable propositions and Gödel's Theorem.	9
2	Wittgenstein and correspondence theories of truth. Stochastic processes. Richard's Paradox and the Paradox of Rosser and Kleene.	11
3	Digital representation of seemingly analog existence. Advantages of digital systems. Digital life.	13
4	Computable recursive functions. Von Neumann and Harvard architectures. Circuit complexity. Instruction set architecture. Processor frontends. Real computation.	15
	<b>II THE PHYSICS OF INFORMATION.</b>	<b>17</b>
5	Information theory of Szilard and Shannon. Entropy and negentropy. Periodic and aperiodic crystals. Digital physics.	19
6	Signals. Sampling theory of Nyquist. The Fourier transform.	21
7	Time's Arrow and the Second Law of Thermodynamics. Heisenberg's uncertainty principle. Landauer's principle. The wrath of Maxwell's Demon.	23
8	The employ of direct currents. Voltage, frequency, resistance, and capacitance. Semiconductors.	25
9	Quantum and optical noise. Leakage and the smallest transistor. Principles of VLSI. Memristors.	27
	<b>III THE ESSENCE AND LIMITS OF COMPUTATION.</b>	<b>29</b>
10	Hierarchy theory of Chomsky. Deterministic and nondeterministic machines. Turing's Machine, Curry's combinatory logic, and Church's $\lambda$ -calculus. The Church-Turing Thesis. Information-theoretic limitations of formal systems.	31
11	Uncomputable functions. Polynomial and Exponential hierarchies. Reductions of Karp and Levin. NP-completeness. Machine-oblivious analysis of algorithms.	33

12	Fixed and floating point. Counting quickly. Numerical approximations and stabilities. Well-conditioned algorithms. The bounding, detection, and correction of errors.	35
13	Computation elements. Real algorithm analysis. Brent's Theorem and Gustafson's Law.	37
14	Lloyd's limit. Kolmogorov complexity, algorithmic information theory and Chaitin's Constant. Schmidhuber's Super- $\Omega$ and Speed Prior.	39
15	Queueing theory of Kleinrock. Baran and distributed communication. Quantum computing, BQP, and spaces of infinitely many dimensions.	41
16	Pseudorandom numbers and pseudorandomized algorithms. The possibility of reversible computation.	43
17	Programming language theory. Compilation. Security and the undecidability of static analysis.	45
18	Code as data. Von Neumann's revenge. Self-modifying code and genetics. Binding and reduction. The joy of LISP. Dijkstra's revenge.	47
	<b>IV THE INELUCTABLE MODALITY OF STATE.</b>	<b>49</b>
19	The persistence of information and remembrance of things past. Search. Data structures.	51
20	Communication networks. Hypercubes, butterflies and banyans.	53
21	Indexing. Fractal structure and Hausdorff dimension of data. Compression. Address spaces and content-addressed memories.	55
22	Memory architecture. Remembering quickly. Offline and online algorithms. Infinite representations.	57
23	The complexity of state and the nature of time. Spacetime and statetime: transformations among space, state and time. Is computation energy?	59
24	Parallelism among bits, registers, instructions, memories, and threads. The Taxonomy of Floyd.	61
25	Dataflow and transport-triggered architectures. Out-of-order processors. Coherent and incoherent memories. SMP and NUMA.	63
26	ACID and relational databases. Transactional memory. Ferromagnetic and plastic-optical storage. The rotting of bits.	65
	<b>V CONSILIENCE.</b>	<b>67</b>
27	Turing dreams he is a machine.	69
28	A machine dreams it is Turing.	71
29	Consilience.	73
30.1	AFTERWARD: The Finest Machine. . . . .	73
30.2	CITATIONS . . . . .	73

---

**EPIGRAMS (fold into ToC, FIXME)**

*PART I: BEYOND THE ZERO.*

“Die ganze Zahl schuf der liebe Gott, alles Ubrige ist Menschenwerk.”  
(“God made integers; all else is the work of man.”)

–Leopold Kronecker, as quoted in H. Weber’s “Leopold Kronecker”,  
*Mathematische Annalen* Vol. 43, No. 1 (1892)

---

*PART II: THE PHYSICS OF INFORMATION.*

“All things physical are information-theoretic in origin, and this is a participatory universe. Observer participancy gives rise to information; and information gives rise to physics.”

–John Archibald Wheeler, *It from Bit* (1989)

---

*PART III: THE ESSENCE AND LIMITS OF COMPUTATION.*

“All physical systems can be thought of as registering and processing information, and how one wishes to define computation will determine your view of what computation consists of.”

–Seth Lloyd, “Ultimate Physical Limits to Computation”,  
*Nature* 406 (2000-08-31)

---

*PART IV: THE INELUCTABLE MODALITY OF STATE*

“μεταβάλλον αναπαύεται.”  
(“Even while it changes, it stands still.”)

–Heraclitus, as quoted in Abelson and Sussman’s  
*The Structure and Interpretation of Computer Programs* (Second Edition, 1996)

---

*PART V: CONSILIENCE.*

“Die Welt ist alles, was der Fall ist. . . Wovon man nicht sprechen kann, darüber muß man schweigen.”  
(“The world is all that is the case. Whereof one cannot speak, one must remain silent.”)

–Ludwig Wittgenstein,  
*Tractatus Logico-Philosophicus* (1918)

---

**Part I**

**BEYOND THE ZERO.**





## Chapter 1

Countable and uncountable numbers.  
Diagonalization. Gödel numbering and  
semiotics. Formally undecidable propositions  
and Gödel's Theorem.



## Chapter 2

Wittgenstein and correspondence theories of truth. Stochastic processes. Richard's Paradox and the Paradox of Rosser and Kleene.



## Chapter 3

Digital representation of seemingly analog existence. Advantages of digital systems. Digital life.



## Chapter 4

Computable recursive functions. Von Neumann and Harvard architectures. Circuit complexity. Instruction set architecture. Processor frontends. Real computation.





## Part II

# THE PHYSICS OF INFORMATION.



## Chapter 5

**Information theory of Szilard and Shannon.  
Entropy and negentropy. Periodic and  
aperiodic crystals. Digital physics.**



## Chapter 6

**Signals. Sampling theory of Nyquist. The Fourier transform.**



## Chapter 7

**Time's Arrow and the Second Law of Thermodynamics. Heisenberg's uncertainty principle. Landauer's principle. The wrath of Maxwell's Demon.**





## Chapter 8

The employ of direct currents. Voltage, frequency, resistance, and capacitance. Semiconductors.



## Chapter 9

**Quantum and optical noise. Leakage and the smallest transistor. Principles of VLSI. Memristors.**



## Part III

# THE ESSENCE AND LIMITS OF COMPUTATION.



## Chapter 10

**Hierarchy theory of Chomsky. Deterministic and nondeterministic machines. Turing's Machine, Curry's combinatory logic, and Church's  $\lambda$ -calculus. The Church-Turing Thesis. Information-theoretic limitations of formal systems.**





## Chapter 11

**Uncomputable functions. Polynomial and Exponential hierarchies. Reductions of Karp and Levin. NP-completeness. Machine-oblivious analysis of algorithms.**



## Chapter 12

**Fixed and floating point. Counting quickly.  
Numerical approximations and stabilities.  
Well-conditioned algorithms. The bounding,  
detection, and correction of errors.**



## Chapter 13

**Computation elements. Real algorithm analysis. Brent's Theorem and Gustafson's Law.**



## Chapter 14

**Lloyd's limit. Kolmogorov complexity, algorithmic information theory and Chaitin's Constant. Schmidhuber's Super- $\Omega$  and Speed Prior.**





## Chapter 15

Queueing theory of Kleinrock. Baran and distributed communication. Quantum computing, BQP, and spaces of infinitely many dimensions.



## Chapter 16

**Pseudorandom numbers and  
pseudorandomized algorithms. The  
possibility of reversible computation.**



## Chapter 17

**Programming language theory. Compilation.  
Security and the undecidability of static  
analysis.**



## Chapter 18

Code as data. Von Neumann's revenge.  
Self-modifying code and genetics. Binding  
and reduction. The joy of LISP. Dijkstra's  
revenge.





Part IV

**THE INELUCTABLE MODALITY OF  
STATE.**



## Chapter 19

**The persistence of information and remembrance of things past. Search. Data structures.**



## Chapter 20

**Communication networks. Hypercubes,  
butterflies and banyans.**



## Chapter 21

**Indexing. Fractal structure and Hausdorff dimension of data. Compression. Address spaces and content-addressed memories.**





## Chapter 22

**Memory architecture. Remembering quickly.  
Offline and online algorithms. Infinite  
representations.**



## Chapter 23

The complexity of state and the nature of time. Spacetime and statetime: transformations among space, state and time. Is computation energy?



## Chapter 24

**Parallelism among bits, registers, instructions, memories, and threads. The Taxonomy of Floyd.**



## Chapter 25

**Dataflow and transport-triggered architectures. Out-of-order processors. Coherent and incoherent memories. SMP and NUMA.**





## Chapter 26

**ACID and relational databases. Transactional memory. Ferromagnetic and plastic-optical storage. The rotting of bits.**



Part V

**CONSILIENCE.**



## Chapter 27

Turing dreams he is a machine.



## Chapter 28

A machine dreams it is Turing.





## Chapter 29

# Consilience.