

Blockchain and Distributed Ledgers

Mathematics, Technology, and Economics

Alexander Lipton

Sila Money, USA & Hebrew University of Jerusalem, Israel

Adrien Treccani

METACO, Switzerland

 **World Scientific**

1 JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

Contents

<i>About the Authors</i>	<i>xi</i>
<i>List of Figures</i>	<i>xxi</i>
<i>List of Tables</i>	<i>xxxiii</i>
<i>List of Abbreviations</i>	<i>xxxvii</i>
<i>Preface</i>	<i>xliii</i>
Background	1
1.1 Introduction	1
1.2 Distributed ledgers in a nutshell	2
1.3 A retrospective view	7
1.4 A perspective view	9
1.5 Book's structure	10
1.6 Summary	10
1.7 Further reading	11
The Global Financial System and its Pain Points	15
2.1 Introduction	15
2.2 Money in retrospective and perspective	15
2.2.1 The role of money	15
2.2.2 Money as objects	16
2.2.3 Paper money	19
2.2.4 Anti-counterfeiting measures	21
2.2.5 Money as records	24
2.2.6 Money and inflation	26
2.2.7 BIS taxonomy of money	26
2.2.8 Where does money come from?	26
2.3 How the financial system operates at the moment	28
2.3.1 Current situation	28
2.3.2 Challenges faced by the current financial system	30
2.3.3 Detailed analysis of money creation	33
2.3.4 Negative interest rates	37
2.3.5 Banking regulations and monetary stability	38
2.3.6 The pros and cons of the current system	38
2.4 Domestic payments	39
2.4.1 The protagonists	39
2.4.2 Settlement	39
2.4.3 Credit card payments	39

2.5	Cross-border payments	41
2.5.1	Cross-border transactions and correspondent banking	41
2.5.2	Forex trading	43
2.5.3	Informal funds transfer systems	44
2.6	Blockchain payments	44
2.7	Summary	46
2.8	Exercises	47
3	A Primer on Cryptocurrencies and Distributed Ledgers	49
3.1	Introduction	49
3.2	Distributed identity	50
3.2.1	Legal identification	50
3.2.2	Digital identification and wallets	51
3.3	Decentralized network	52
3.3.1	Client-server model	52
3.3.2	Peer-to-peer model	53
3.3.3	Network nodes	54
3.3.4	Bootstrapping of a node	55
3.4	Distributed ledger	56
3.4.1	Permissioning framework	56
3.4.2	Blockchain data structure	56
3.5	Double spending	58
3.5.1	Illustration in a centralized setup	58
3.5.2	Illustration in a decentralized setup	59
3.6	Network consensus	60
3.6.1	Sybil attacks	61
3.6.2	Digital work with a proof-of-work	62
3.6.3	Building the chain	63
3.6.4	Block rewards and miners	63
3.6.5	A computational power race	64
3.6.6	Difficulty under competition	65
3.6.7	Forks and consensus chain	66
3.6.8	The 51% attack	67
3.6.9	Confirmations and finality	69
3.6.10	The limits of proof-of-work	69
3.6.11	Staking as an alternative to working	70
3.7	Path to the after-Bitcoin	70
3.7.1	Pizza day	70
3.7.2	Silk Road	71
3.7.3	Altcoins	72
3.7.4	Ethereum and smart contracts	73
3.7.5	Tokenization	74
3.7.6	Initial coin offerings	75
3.7.7	Decentralized finance and autonomous organizations	76
3.8	Summary	77
3.9	Exercises	77

4	Essential Cryptographic Tools	79
4.1	Introduction	79
4.2	Symmetric key cryptography	81
4.2.1	Introduction	81
4.2.2	Caesar's cipher	82
4.2.3	Affine cipher	82
4.2.4	A simple substitution cipher	83
4.2.5	The Vigenère cipher	83
4.2.6	The Enigma machine	83
4.2.7	A one-time pad	85
4.2.8	A stream cipher	85
4.2.9	Data encryption standards	86
4.3	Asymmetric key cryptography	86
4.3.1	Introduction	86
4.3.2	Cryptographic one-way functions	88
4.3.3	Abstract encryption-decryption algorithm	88
4.3.4	Abstract digital signature algorithm	88
4.3.5	Abstract secret-sharing algorithm	89
4.4	Elements of number theory	90
4.4.1	The set of integers modulo n	90
4.4.2	The Euclidean algorithm	90
4.4.3	The extended Euclidean algorithm	91
4.4.4	Fermat's little theorem	91
4.4.5	Euler's theorem	92
4.5	Finite ring cryptography	92
4.5.1	Modular exponentiation	92
4.5.2	A good trapdoor function?	93
4.5.3	A good trapdoor function!	93
4.5.4	RSA encryption-decryption algorithm	94
4.5.5	RSA digital signature algorithm	94
4.5.6	Blind digital signature algorithm	96
4.5.7	Chaum's anonymous cash	97
4.6	Finite field cryptography	98
4.6.1	Definitions	98
4.6.2	Primitive roots	99
4.6.3	ElGamal encryption algorithm	100
4.6.4	ElGamal digital signature algorithm	101
4.6.5	Schnorr digital signature algorithm	103
4.6.6	Diffie-Hellman key exchange	105
4.7	Elliptic Curve Cryptography	106
4.7.1	Continuous elliptic curves	106
4.7.2	Historical aside	108
4.7.3	Addition on elliptic curves	111
4.7.4	Projectivization of elliptic curves	115
4.7.5	Multiplication on elliptic curves	115
4.7.6	Discrete elliptic curves	116
4.7.7	The discrete log problem on elliptic curves	120
4.7.8	The standard elliptic curve secp256r1	122
4.7.9	Elliptic curve digital signature algorithm	123

4.7.10	Elliptic curve Schnorr digital signature algorithm	125
4.7.11	Diffie-Hellman key exchange	126
4.8	Comparison of different digital signature algorithms	126
4.9	Cryptographic hash functions	127
4.9.1	Hash functions	127
4.9.2	Collision-resistant hash functions	127
4.9.3	Signatures and hash functions	128
4.9.4	Signatures and birthday attacks	128
4.9.5	The random oracle hash	129
4.9.6	A practical hash function	130
4.9.7	Search puzzles and hash functions	130
4.9.8	Other uses of cryptographic hash functions	131
4.9.9	Iterative hash function with padding	131
4.10	Secure hash algorithms	132
4.10.1	Background	132
4.10.2	MD5	132
4.10.3	SHA-256	134
4.10.4	RIPEMD-160	137
4.11	Merkle trees and hash pointers	138
4.11.1	Merkle trees	138
4.11.2	Hash pointers and chain signatures	138
4.11.3	Chain signatures combined with Merkle trees	139
4.12	Quantum-resistant cryptography	141
4.13	Summary	142
4.14	Exercises	143
5	Bitcoin — A Deep Dive	145
5.1	Introduction	145
5.2	Bitcoin addresses	147
5.3	Transactions	153
5.3.1	Distributed ledger accounting	153
5.3.2	Bitcoin transactions and mathematical induction	155
5.3.3	Transaction structure	156
5.3.4	Transaction scripts	159
5.3.5	Transaction verification	161
5.3.6	Representative transactions	161
5.3.7	Transaction broadcast	169
5.3.8	The Coinbase transaction	171
5.4	The Bitcoin ecosystem	174
5.4.1	Full node	174
5.4.2	Simplified payment verification node	174
5.4.3	Wallet	175
5.4.4	Solo miners	175
5.4.5	Mining pools	175
5.4.6	Exchanges	176
5.4.7	Bitcoin tumblers or mixers	176
5.5	Mining	177
5.5.1	Consensus	177
5.5.2	How Bitcoin rewards miners?	179

5.5.3	How do miners mine?	184
5.5.4	Mining difficulty	187
5.5.5	Pooling of resources	190
5.5.6	Malicious attacks	193
5.5.7	Soft and hard forks	195
5.5.8	Growing blockchain by induction	196
5.6	Anatomy of Block 600,000	198
5.7	Bitcoin pros and cons	199
5.8	Summary	202
5.9	Exercises	202
6	Ethereum — A Distributed World Computer?	205
6.1	Introduction	205
6.2	Similarities and differences between Bitcoin and Ethereum	207
6.3	A more centralized protocol?	208
6.4	Ethereum account types	209
6.5	The Ethereum Virtual Machine	211
6.6	Transfers and smart contract calls	211
6.7	Consensus	214
6.8	Smart contracts	217
6.8.1	Definitions	217
6.8.2	Example — A forward contract	220
6.8.3	Advantages and disadvantages of smart contracts	221
6.8.4	Oracles	223
6.9	Applications of Ethereum smart contracts	224
6.9.1	Potential use cases	224
6.9.2	Tokens and token standards	224
6.9.3	Crowdfunding via initial coin offerings	226
6.9.4	Stablecoins	227
6.9.5	Automated market makers	227
6.9.6	Decentralized autonomous organizations	229
6.10	Summary	231
6.11	Exercises	232
7	Ripple — A Simple Solution to a Complex Problem?	233
7.1	Introduction	233
7.2	Ripple protocol	233
7.3	Applications	238
7.4	Summary	242
7.5	Exercises	242
8	Central Bank Digital Currencies and Stablecoins	243
8.1	Introduction	243
8.2	Narrow banks	244
8.2.1	A brief history	244
8.2.2	Possible designs of a narrow bank	246

8.3	CBDC	247
8.3.1	Central banks as issuers of CBDC	247
8.3.2	Narrow banks as issuers of CBDC	247
8.3.3	Technical considerations	248
8.4	Stablecoins	249
8.4.1	Background	249
8.4.2	Stablecoins fully collateralized with fiat	250
8.4.3	Coins partially collateralized with fiat	252
8.4.4	Coins (over)collateralized with crypto	253
8.4.5	Dynamically stabilized coins	254
8.5	Digital trade coins collateralized with assets	256
8.5.1	General considerations	256
8.5.2	How to build a DTC	257
8.6	Summary	259
8.7	Exercises	259
9	Wallets and Key Management	261
9.1	Introduction	261
9.2	General wallet architecture	264
9.2.1	Necessary components	264
9.2.2	Network node	264
9.2.3	Blockchain indexer	265
9.2.4	Wallet application	266
9.2.5	Keystore	266
9.3	Wallet genesis	267
9.3.1	Key space	267
9.3.2	Brain wallet	268
9.3.3	The need for entropy	270
9.3.4	A concrete collision attack	270
9.3.5	True random number generators	271
9.4	Deterministic key derivation	272
9.4.1	The need for multiple keys	272
9.4.2	The original Bitcoin Core approach	272
9.4.3	BIP32	272
9.4.4	BIP44	277
9.4.5	Extensions to BIP32	278
9.5	From mnemonic to seed	279
9.5.1	Export and human-readability	279
9.5.2	BIP39	279
9.6	The relativity of security	282
9.6.1	Custodial wallet services	282
9.6.2	A practical example	283
9.6.3	The Binance hack	284
9.6.4	The QuadrigaCX fraud	285
9.7	Key isolation and transaction approval	286
9.7.1	Security ingredients	286
9.7.2	Hot and cold storage	286
9.7.3	Four-eyes principle	287
9.7.4	Off-chain validation	287

9.7.5	On-chain validation	288
9.7.6	Multi-party computation	288
9.8	Summary	289
9.9	Exercises	289
10	Cryptocurrencies and Quantitative Finance	291
10.1	Introduction	291
10.2	Can cryptocurrencies be viewed as money?	292
10.3	Do fair prices of cryptocurrencies exist?	292
10.4	Distribution of daily BTC returns	293
10.5	Distribution of yearly BTC returns	306
10.5.1	The Fourier transform	306
10.5.2	Monte Carlo simulations	310
10.6	Distribution of daily ETH, XRP, and MRKT returns	311
10.7	Comparative statistics of cryptocurrency returns	325
10.8	Cryptocurrency ecosystem and its ecology	328
10.9	BTC valuation models	330
10.10	Bitcoin dominance index	339
10.10.1	The SIR model	339
10.10.2	The SIS model	340
10.11	Automated market makers	344
10.12	Summary	353
10.13	Exercises	353
11	Current Research Topics	355
11.1	Introduction	355
11.2	Intra- and interoperability	356
11.2.1	Background	356
11.2.2	Intraoperability	356
11.2.3	Interoperability	357
11.3	Privacy	360
11.3.1	Background	360
11.3.2	Payment channels	361
11.3.3	Coin mixing	362
11.3.4	Built-in cryptographic obfuscation	364
11.4	Scalability trilemma	365
11.4.1	Background	365
11.4.2	Current transactional banking model: scalable + secure	366
11.4.3	Current crypto model: decentralized + secure	367
11.4.4	Future fintech model: decentralized + scalable + secure	367
11.5	Summary	374
11.6	Exercises	374
12	Present and Future of DLT	377
12.1	Introduction	377
12.2	Financial Services	379

12.2.1	Accounting and audit	379
12.2.2	Global payments	382
12.2.3	Programmable money	384
12.2.4	Regulations	387
12.2.5	Trade execution, clearing and settlement	388
12.3	Government	390
12.3.1	Identity	390
12.3.2	Voting	394
12.4	Healthcare	396
12.4.1	Electronic health records system	396
12.4.2	Research	398
12.4.3	Supply chain	399
12.5	Supply chain	400
12.5.1	Supply chain management	400
12.5.2	Trade finance	401
12.6	Tokenization of real assets	403
12.7	Summary	404
12.8	Exercises	405
	<i>Bibliography</i>	407
	<i>Name Index</i>	425
	<i>Subject Index</i>	427