A
Accessible region (AR), 8, 9
Adiabatic capacitive logic (ACL), 213–216
Adiabatic circuit approaches
adiabatic capacitive logic, 213–216
asymptotically adiabatic, 197
Bennett clocking, 199–200
Boltzmann tail, 196
ferro-electric FETs, 196
field-effect transistors, 196
Fredkin and Toffoli gates, 194–195
low-loss reversible logic, 195
microprocessor (see Adiabatic microprocessor)
molecular quantum-dot cellular automata, 216–219
on-chip measurement
Au-Pt thermocouples, 223–224
commercial bismuth telluride Peltier cooler, 219
COMSOL multiphysics software, 221
Ni-Au thermocouple, 220–221
simulated thermal response, 224–225
temperature distribution, 225–226
TFTCs, 219
PFAL AND gate, schematic of, 197–198
quasi-adiabatic processes, 195, 197
RC time constant, 195
reversible computing system, 194
single polarity power clock, 196–197
tunnel FETs, 196
voltage waveforms, 196–198
Adiabatic inverter, 211
Adiabatic microprocessor, 212
architecture, 200–203
CMOS design tools
Bennett energization sequence checker, 204, 206
Bennett placement constraints, 206–208
Bennett wrappers package, 204
circuit architecture, 209
design entry and logic synthesis, 206
energy-recovery logic, 202
execution test program, 204, 205
interfacing sequential logic, 208–209
main components of, 202
ramp logic timing simulation environment, 204
standard logic synthesis and integration, 206, 207
standard place-and-route tool, 208
standard cell design and simulation
2-input AND, 209
2-input NOR, 209
2-input OR, 209
2-input XOR, 209
layouts, 210–212
logic gates and transfer gate-based designs, 209
NAND gates, 209
SPICE simulation, 210
test-framework, 209
Adiabatic reversible computing, 183
AND gate, 111
Asymmetric memory, 120–121
Asymptotically adiabatic, 197
Autonomous Maxwell demon, 163–165
Encoding scheme, 4, 5, 36

Energy in computation
  adiabatic reversible computing, 183
  CMOS transistor gates, 178
  CPU energy efficiency, 178
  dark silicon, 181
  EDA metric, 182, 183
  energy recovery, 180–181
  FETs, 179
  Landauer Limit, 178
  Moore’s law, 182
  reversible computing, 180–181
  USL, 178

  Efficiency, 192
  Helmholtz free energy, 25
  information energy cost, 170–173
  nonequilibrium free energy, 109, 119, 132
  physical energy, 150

Entropy
  concept of, 142
  definition, 6
  encoding, 73
  and energy, 150
  internal, 120
  for known/unknown bit, 38
  physical, 118
  preparation, 73
  production, 104, 110, 119
  Shannon, 117
  SMI (see Shannon measure of information (SMI))
  total entropy, 117–118
  von Neumann entropy, 6, 53–54, 61, 86
    grouping property of, 97–98
    subadditive, 70, 96
    unitary-similarity transformations, 97

ERASE gate, 111

Erasure conditional
  average environmental energy, 70
  energy dissipation, 93–94
  erase with copy operation, 71, 80
  initial and final state entropy, 70
  Landauer-Bennett limit, 71
  Partovi’s inequality, 70, 97
  pre-erasure system states, 70, 71, 74
  unitary evolution operators, 70
  von Neumann entropy, 70, 97

  dissipationless erasure, 87
  information, 114
  asymmetric memory, 120
  ERASE WITH COPY operations, 71

Landauer bound, 102
Landauer erasure attributable, 74
standard state, 111
two-box model, 114
irreversible information, 116
Landauer (see Landauer erasure)
in minimal system
  encoding information, physical states,
  36–37
  entropy for known/unknown bit, 38
  erasure of known/unknown bit, 42–46
  writing a bit, 40–41, 43
  optimal information-erasure protocol, 120
  quasi-static erasure protocol, 121

F
  Fermi-Dirac distribution, 29
  Ferro-electric gate (FETs), 179
  Fluctuation theorem, 101, 107
  Fredkin gate, 194–195

H
  Hamiltonian dynamics, 109
  Hardware description language (HDL), 206
  Heat emission, 103, 110, 114–116, 122
  Heat flow, 6, 156, 159, 221
  Heat transfer
    binary memory, 103
  Helmholtz free energy, 25
  Hilbert space, 46, 84

I
  Inequality, 120, 125, 126, 132, 134
  Information energy cost, 170–173
  Information entropy, 142, 150, 156
  Information erasure, 114
  asymmetric memory, 120
  ERASE WITH COPY operations, 71
  Landauer bound, 102
  Landauer erasure attributable, 74
  standard state, 111
two-box model, 114
Internal entropy, 118, 120, 122
Irreversible information erasure, 116

J
  Jarzynski equality, 163, 166, 171–173
  Jaynes maximum entropy principle, 6, 15, 30, 61
  Jensen’s inequality, 172
**K**

Known data, 75–78, 93–95

Kronecker’s delta, 124

**L**

Lagrange equation, 38

Lagrange multipliers, 15–17, 20, 38

Landauer-Bennett limit, 82, 94–95

  - direct proofs, 88
  - erase with copy operation, 71
  - indirect proofs, 89–91
  - irreversible erasure processes, 65
  - vs. Landauer limit, 66
  - QCA ERASE WITH COPY operation, 79–81
  - reversible erasure processes, 65–66
  - thermodynamic proofs, 83–86

Landauer bound, 114, 166, 167, 169, 171–173

Landauer erasure, 66

  - conditional erasure
    - average environmental energy, 70
    - energy dissipation, 93–94
    - erase with copy operation, 71, 80
    - initial and final state entropy, 70
    - Landauer-Bennett limit, 71
    - Partovi’s inequality, 70, 97
    - pre-erasure system states, 70, 71, 74
    - unitary evolution operators, 70
    - von Neumann entropy, 70, 97
    - conditioning and copies, roles of, 87–88
    - energy cost, 68–69
    - known, unknown, and random/no data, 75–79

Landauer and Landauer-Bennett limits, 94–95

  - conditioning and copies, roles of, 87–88
  - direct proofs, 88
  - indirect proofs, 89–91
  - QCA ERASE WITH COPY operation, 79–81
  - quantum dynamical proofs, 84
  - thermodynamic proofs, 83–86

OLR information, 96

  - physical state transformations, 67–68
  - in thermodynamics
    - Landauer limit, 84, 86
    - probability and information, 85–86
    - quantum dynamical proofs, 84
    - random data state, 84–85
    - Shannon entropy, 86
    - Szilard engine, 83, 84
    - von Neumann entropy, 86

  - unconditional erasure
    - density operator, 73
    - energy cost, 72
    - energy dissipation, 93–94
    - experiments, 92–93
    - feature of, 72
    - Landauer cost, 74, 82
    - Landauer’s limit, 74, 82
    - physical costs, 74, 80
    - resetting of system to standard state, 71
    - Shannon entropy, 73–74
    - single state transformation, 72–73
    - “surrogate” state transformation, 73
    - thought experiments, 71–72
    - unitary operation, 72
    - unitary similarity transformations, 72

Landauer limit, 65, 84, 94–95

  - conditioning and copies, roles of, 87–88
  - direct proofs, 88
  - indirect proofs, 89–91
  - vs. Landauer-Bennett limit, 66
  - thermodynamic proofs, 83–86
  - unconditional erasure, 74

Landauer’s erasure principle, 158–159

Landauer’s principle (LP), 6, 61, 102, 113–117, 120, 178

  - assertion, 193
  - ceramic disk capacitor, 185
  - COPY–ERASE WITH A COPY experiment, energy balance for, 190–191
  - COPY–ERASE WITH A COPY experiment, waveforms for, 189–190

  - copy operation, 183–184
  - erase operation, 183–184
  - ERASE WITHOUT A COPY experiment, 191, 192

  - erasure in minimal system
    - encoding information, physical states, 36–37
    - entropy for known/unknown bit, 38
    - erasure of known/unknown bit, 42–46
    - writing a bit, 40–41, 43

  - Gaussian noise, 188
  - heat dissipation, 31–32, 65
  - input measurement amplifier noise, 188
  - irreversible bit manipulation, 183
  - many-to-one bit erasure process, 32–34
  - measurement system, 187
  - neuromorphic and analog computing, 180
  - physics of information, 158–159
  - experimental verification of, 165–166
  - quantum setting, 168
ramp process, 186
reversibility, 5
second law of thermodynamics, 34–35
thermally activated error, 185
thermodynamic entropy, 83
voltage across resistor, 186
voltage fluctuations, 186
voltage ramps, 185
Langevin dynamics, 109
Langevin equation, 108, 114
Laplace’s demon, 3–4, 8, 51
Laptop computers, 178
Least significant bit (LSB), 188
Lindblad formalism, 54
Logical reversibility, 102, 111–113
binary memory, 103
LPNSG method, 89

M
Macroscopic effect, 105
Man-made computers, 169
Markov jump processes, 108, 109, 130
Maxwell’s demon, 79, 86, 101, 102, 104, 144, 152–153
entropy balance
bipartite Markov jump process, 130
fundamental energy cost, 129
Langevin system, 130
Shannon entropy, 129–130
total entropy production, 130
feedback control
conditional distribution, 124
conditional entropy, 123
equilibrium free energy, 126
heat engine, 122
Kronecker’s delta, 124
mutual information, 123
nonequilibrium free energy, 125
Szilard engine, 123, 125
physics of information, 156–158
autonomous, 163–165
cool atoms, 160–161
quantum regime, 167–168
Mean-square velocity, 156
Microcanonical ensemble, 15–16
Molecular quantum-dot cellular automata, 216–219
Moore’s law, 182

N
Newtonian mechanics, 104
Noise spectral densities (NSD), 187, 191
Nonequilibrium free energy, 109, 119, 132
Norton, John D., 66, 83–90
NOT gate, 111
Nuclear magnetic resonance (NMR), 167

O
Observer-local referential (OLR) information, 96
One-to-one mapping, 159, 165
Optimal information-erasure protocol, 120, 121

P
Partovi’s inequality, 70, 73, 97
Physical energy, 150
Physical entropy, 118, 142, 150
vs. information entropy, 147–149
Physics of information
Landauer’s principle, 158–159
experimental verification of, 165–166
quantum setting, 168
Maxwell’s demon, 156–158
autonomous, 163–165
cool atoms, 160–161
quantum regime, 167–168
Szilard engine, 156–158
experimental realization of, 161–163
Planck’s constant, 30
Positive feedback adiabatic logic (PFAL), 197
Power dissipation
Au-Pt thermocouples, 223–224
commercial bismuth telluride Peltier cooler, 219
COMSOL multiphysics software, 221
Ni-Au thermocouple, 220–221
simulated thermal response, 224–225
temperature distribution, 225–226
TFTCs, 219
Probability, 7–9
Proofs
direct, 88
indirect, 89–91
quantum dynamical proofs, 84
thermodynamical, 83–86

Q
Quantum-dot-cellular automata (QCA) scheme, 36, 79–81, 216–219
Quantum Landauer’s principle, 168
Quantum Liouville equation, 54
<table>
<thead>
<tr>
<th>Page</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum mechanics, 104</td>
<td>encoding probabilities</td>
</tr>
<tr>
<td>density matrix</td>
<td>statistical mechanics, 31</td>
</tr>
<tr>
<td>coherences, 54</td>
<td>unconditional erasure, 73–74, 86</td>
</tr>
<tr>
<td>global system, 51–53</td>
<td>Landauer-like bounds, 66</td>
</tr>
<tr>
<td>Hermitian, 53</td>
<td>mutual information, 130</td>
</tr>
<tr>
<td>open quantum systems, statistical mechanics for, 54–55</td>
<td>probability distribution, 117</td>
</tr>
<tr>
<td>time development of, 54</td>
<td>unique probability distribution, 61</td>
</tr>
<tr>
<td>von Neumann entropy, 53–54, 61</td>
<td>Shannon measure of information (SMI), 6</td>
</tr>
<tr>
<td>ideal quantum gas, free expansion of, 56–60</td>
<td>continuous probability density, 9–10</td>
</tr>
<tr>
<td>physical system</td>
<td>canonical ensemble, 17–21</td>
</tr>
<tr>
<td>separability of, 3</td>
<td>information gain, 13</td>
</tr>
<tr>
<td>state vector, 46</td>
<td>question game, 11–13</td>
</tr>
<tr>
<td>quantum entropy of outcomes, 55–56, 62</td>
<td>quantum mechanics, eigenvalues</td>
</tr>
<tr>
<td>quantum formalism and probabilities, 46–47</td>
<td>particles position, 49</td>
</tr>
<tr>
<td>SMI, eigenvalues</td>
<td>time dependence, 49–51</td>
</tr>
<tr>
<td>particles position, 49</td>
<td>two-state system, 47–49</td>
</tr>
<tr>
<td>time dependence, 49–51</td>
<td>wavefunction and probability distribution, 49, 50</td>
</tr>
<tr>
<td>two-state system, 47–49</td>
<td>statistical mechanics (see Statistical mechanics)</td>
</tr>
<tr>
<td>wavefunction and probability distribution, 49, 50</td>
<td>Single electron transistor (SET), 163, 165</td>
</tr>
<tr>
<td>Quasi-adiabatic circuits, 197</td>
<td>Split-rail charge recovery logic (SCRL), 198</td>
</tr>
<tr>
<td>Quasi-static erasure protocol, 115, 121</td>
<td>Statistical mechanics, 21, 61</td>
</tr>
<tr>
<td>Quasi-static protocol, 115–116</td>
<td>canonical ensemble</td>
</tr>
<tr>
<td>R</td>
<td>chemical potential, 27, 28</td>
</tr>
<tr>
<td>Random data, 75, 77, 78, 84</td>
<td>external work, 26–27</td>
</tr>
<tr>
<td>Raw information, 36</td>
<td>free energy expression, 28</td>
</tr>
<tr>
<td>conserved, 3–4</td>
<td>non-interacting fermions and bosons, 28–29</td>
</tr>
<tr>
<td>separability, 2–3</td>
<td>thermal bath, 22–26</td>
</tr>
<tr>
<td>Reversibility, 102</td>
<td>open quantum systems, 54–55</td>
</tr>
<tr>
<td>in computation, 111–113</td>
<td>system microstates, 29–31</td>
</tr>
<tr>
<td>in conventional thermodynamics, 104–107</td>
<td>Stochastic thermodynamics, 101, 170–173</td>
</tr>
<tr>
<td>in stochastic thermodynamics, 107–110</td>
<td>reversibility in, 107–110</td>
</tr>
<tr>
<td>thermodynamic</td>
<td>Symmetric memory, 120</td>
</tr>
<tr>
<td>binary memory, 103</td>
<td>Szilard engine</td>
</tr>
<tr>
<td>feedback control, 126–129</td>
<td>analogue of, 127</td>
</tr>
<tr>
<td>S</td>
<td>Brownian particle, 123</td>
</tr>
<tr>
<td>Sakur-Tetrode equation, 29–30</td>
<td>encode binary data, 76</td>
</tr>
<tr>
<td>Schrödinger equation, 50, 54</td>
<td>entropy balance, 134</td>
</tr>
<tr>
<td>Second law, 102</td>
<td>Landauer limit, 88</td>
</tr>
<tr>
<td>of thermodynamics, 34–35</td>
<td>one-bit memory, 79</td>
</tr>
<tr>
<td>conventional, 104–105</td>
<td>physics of information, 156–158</td>
</tr>
<tr>
<td>stochastic, 108–110</td>
<td>experimental realization of, 161–163</td>
</tr>
<tr>
<td>total entropy production, 132, 133</td>
<td>quantum analogues, 136</td>
</tr>
<tr>
<td>Shannon entropy (SMI)</td>
<td>schematic of, 123, 130–131</td>
</tr>
<tr>
<td>arbitrary probability distribution, 107</td>
<td>thermodynamic reversibility, 127</td>
</tr>
</tbody>
</table>
T
Thermal fluctuations, 3, 41, 46, 83, 103, 107, 172
Thermodynamic entropy, 6, 23–24, 29, 30, 38, 104, 147
Thermodynamic identity, 25–26
Thermodynamic quantities
bit operations, 38–40
  erasure of known/unknown bit, 42–46
  writing a bit, 40–41, 43
Thermodynamic reversibility, 102
  binary memory, 103
  feedback control, 126–129
Thermodynamics
  of computation
    asymmetric memory, 120–121
    canonical distribution, 119
    conditional probability, 117
    entropy and energy, 150
    entropy, concept of, 142
    entropy production, 119
    heat emission, 122
    inconsistencies and contradictions, 146–147
    internal entropy, 120
    Landauer principle, 116–117, 120
    Landauer’s original arguments, 145–146
    Landauer’s principle, 151–152
    Maxwell’s demon, 152–153
    model of, 143–145
    nonequilibrium free energy, 119
    optimal information-erasure protocol, 120
    physical entropy, 118
    physical entropy vs. information entropy, 147–149
    quasi-static erasure protocol, 121
    reversibility, concept of, 142
    Shannon entropy, 117
    stochastic computing, 151
    string of bits, 150
    total entropy, 117–118
    Turing machine, 142
    conventional, 104–107
    of information, 101, 102
    Landauer erasure
      Landauer limit, 84, 86
      probability and information, 85–86
      quantum dynamical proofs, 84
      random data state, 84–85
      Shannon entropy, 86
      Szilard engine, 83, 84
      von Neumann entropy, 86
    second law of, 34–35, 156
    stochastic, 101, 107–110, 170–173
      measurement and feedback processes, 130–131
      mutual information, 132
      reversibility in, 107–110
Thin film thermocouples (TFTCs), 219
Toffoli gate, 194–195
Total entropy, 113, 118, 130, 132–134
Total (physical) entropy, 117–118
Transfer gate (TG)-based multiplexers, 209
Turing-machine model, 142–144, 146
Two-box model, 114–115
Two-state system, 48, 151, 156, 157

U
Ultimate Shannon Limit (USL), 178, 183, 184, 193
Unconditional Landauer erasure
  density operator, 73
  energy cost, 72
  energy dissipation, 93–94
  experiments, 92–93
  feature of, 72
  Landauer cost, 74, 82
  Landauer’s limit, 74, 82
  physical costs, 74, 80
  resetting of system to standard state, 71
  Shannon entropy, 73–74
  single state transformation, 72–73
  “surrogate” state transformation, 73
  thought experiments, 71–72
  unitary operation, 72
  unitary similarity transformations, 72
  Unitary-similarity transformations, 72, 97

V
Voltage across resistor, 186
von Neumann entropy, 6, 53–54, 61, 86
  grouping property of, 97–98
  subadditive, 70, 96
  unitary-similarity transformations, 97