# The Physics of Information Technology

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# Contents

# 2 Interactions, Units, and Magnitudes

Modern information technology operates over a spectacular range of scales; bits from a memory cell with a size of $10^{-7}$ meters might be sent $10^{7}$ meters to a geosynchronous satellite. It is important to be comfortable with the orders of magnitudes and associated interaction mechanisms that are useful in practice. Our first task will be to review the definitions of important units, then survey the types of forces, and finally look at typical numbers in various regimes.

## 2.1 UNITS

Many powers of ten have been named because it is much easier to say something like "a femtosecond optical pulse" than "a 0.000 000 000 000 001 second optical pulse" when referring to typical phenomena at that scale (a cycle of light takes on the order of a femtosecond). The dizzying growth of our ability to work with large and small systems pushes the bounds of this nomenclature; data from terabyte storage systems is read out into femtofarad memory cells. It is well worth memorizing the prefixes in Table 2.1.

Table 2.1. *Orders of magnitude.*

| Magnitude | Prefix | Symbol | Magnitude | Prefix | Symbol |
|---|---|---|---|---|---|
| $10^{-24}$ | yocto | y | $10^{24}$ | yotto | Y |
| $10^{-21}$ | zepto | z | $10^{21}$ | zetta | Z |
| $10^{-18}$ | atto | a | $10^{18}$ | exa | E |
| $10^{-15}$ | femto | f | $10^{15}$ | peta | P |
| $10^{-12}$ | pico | p | $10^{12}$ | tera | T |
| $10^{-9}$ | nano | n | $10^{9}$ | giga | G |
| $10^{-6}$ | micro | $\mu$ | $10^{6}$ | mega | M |
| $10^{-3}$ | milli | m | $10^{3}$ | kilo | k |
| $10^{-2}$ | centi | c | $10^{2}$ | hecto | h |
| $10^{-1}$ | deci | d | $10^{1}$ | deka | da |

Physical quantities must of course be measured in a system of units; there are many alternatives that are matched to different regimes and applications. Because of their interrelationships it is necessary only to define a small number of fundamental quantities to be able to derive all of the other ones. The choice of which fundamental definitions to use changes over time to reflect technological progress; once atomic clocks made it possible to measure time with great *precision* (small variance) and *accuracy* (small bias), it became more reliable to define the meter in terms of time and the speed of light rather than a reference bar kept at the Bureau International des Poids et Mesures (BIPM, `http://www.bipm.org`) in Sevres, France. The kilogram is still defined in terms of a platinum–iridium cylinder held at BIPM instead of a fundamental physical process, a source of great frustration in the metrology community. Aside from the difficulty in duplicating it, the accumulation of contaminants on the surface increases the mass by about 1 part in $10^9$ per year, requiring that it be measured only after a special cleaning procedure [Girard, 1994].

The most common set of base defined quantities in use is the *Système International d'Unités* (*SI*) [BIPM, 1998]:

length: *meter* (m)
: The meter is the length of path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

mass: *kilogram* (kg)
: The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

time: *second* (s)
: The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

current: *ampere* (A)
: The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to $2\times10^{-7}$ newtons per meter of length. (See Problem 6.4.)

temperature: *kelvin* (K)
: The kelvin, the unit of thermodynamic temperature, is the fraction of 1/273.16 of the thermodynamic temperature of the triple point of water . (Temperatures in degrees Celsius are equal to temperatures in Kelvin + 273.15. The triple point is the temperature and pressure at which the liquid, solid, and gas phases of water co-exist. It is fixed at 0.01 °C, and provides a more reliable reference than the original centigrade definition of 0 °C as the freezing point of water at atmospheric pressure.)

quantity: *mole* (mol)
: The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12 (i.e., Avogadro's constant $6.022\ldots\times10^{23}$).

intensity: *candela* (cd)
: The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540\times10^{12}$ hertz and that has a radiant intensity in the direction of 1/683 watts per steradian. (The frequency corresponds to the wavelength of 555 nm where the eye is most sensitive, the

factor of 683 comes from matching an earlier definition based on the emission from solidifying platinum, and a steradian is the solid angle subtended by a unit area on the surface of a sphere with unit radius; see Chapter 12 for more on luminosity.)

From these seven fundamental units many other ones are derived in terms of them, including:

capacitance: *farad* F ($m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$)
: The farad is the capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.

charge: *coulomb* C ($A \cdot s$)
: The coulomb is the quantity of electricity transported in 1 second by a current of 1 ampere.

energy: *joule* J ($m^2 \cdot kg \cdot s^{-2}$)
: The joule is the work done when the point of application of a force of 1 newton is displaced a distance of 1 meter in the direction of the force. (Remember that energy equals force times distance.)

force: *newton* N ($m \cdot kg \cdot s^{-2}$)
: The newton is that force which, when applied to a body having a mass of 1 kilogram, gives it an acceleration of 1 meter per second squared. (Remember that force equals mass time acceleration.)

illuminance: *lux* lx ($cd \cdot m^{-2}$)
: The lux is equal to an illuminance of 1 lumen per square meter.

inductance: *henry* H ($m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$)
: The henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second.

luminous flux: *lumen* lm (cd)
: The lumen is the luminous flux emitted within a unit solid angle of 1 steradian by a point source having a uniform intensity of 1 candela.

magnetic flux: *weber* Wb ($m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$)
: The weber is the magnetic flux which, linking a circuit of 1 turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second.

magnetic flux density: *tesla* T ($kg \cdot s^{-2} \cdot A^{-1}$)
: The tesla is the magnetic flux density given by a magnetic flux of 1 weber per square meter.

power: *watt* W ($m^2 \cdot kg \cdot s^{-3}$)
: The watt is the power which gives rise to the production of energy at the rate of 1 joule per second.

pressure: *pascal* Pa ($m^{-1} \cdot kg \cdot s^{-2}$)
: The pascal is the pressure of 1 newton per square meter.

potential: *volt* V ($m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$)
: The volt is the difference of electric potential between two points of a conductor

Table 2.2. *Selected conversion factors.*

| | | |
|---|---|---|
| 1 dyne $(\mathrm{gm \cdot cm \cdot s^{-2}})$ | = | $1\times10^{-5}$ N |
| 1 erg $(\mathrm{gm \cdot cm^2 \cdot s^{-2}})$ | = | $1\times10^{-7}$ J |
| 1 horsepower (hp) | = | 745.7 W |
| 1 atmosphere (atm) | = | 101325 Pa |
| 1 ton (short) | = | 2000 pounds |
| | = | 907.18474 kg |
| 1 electron volt (eV) | = | $1.602176462\times10^{-19}$ J |
| 1 amu | = | $1.66053873\times10^{-27}$ kg |
| 1 angstrom (Å) | = | $1\times10^{-10}$ m |
| 1 fermi (fm) | = | $1\times10^{-15}$ m |
| 1 parsec (pc) | = | $3.085678\times10^{16}$ m |
| 1 mile (mi) | = | 1609.344 m |
| 1 foot (ft) | = | 0.3048 m |
| 1 inch (in) | = | 0.0254 m |
| 1 liter (L) | = | 0.001 $\mathrm{m^3}$ |
| 1 pound (lb) | = | .45359237 kg |
| 1 pound-force (lbf) | = | 4.44822 N |

carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

resistance: *ohm* $\Omega$ $(\mathrm{m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}})$

The ohm is the electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere. (These derivative definitions of the volt and ohm have more recently been replaced by fundamental ones fixing them in terms of the voltage across a *Josephson junction* and the resistance steps in the *quantum Hall effect* [Zimmerman, 1998], and capacitance may be defined by counting electrons on a *Single-Electron Tunneling* (*SET*) device [Keller *et al*., 1999].)

It is important to pay attention to the units in these definitions. Many errors in calculations can be caught by making sure that the final units are correct, and it can be possible to make a rough estimate of an answer to a problem simply by collecting relevant terms with the right units (this is the subject of *dimensional analysis*). Electromagnetic units are particularly confusing; we will consider them in more detail in Chapter 6. The SI system is also called *MKS* because it bases its units on the meter, the kilogram, and the second. For some problems it will be more convenient to use *CGS* units (based on the centimeter, the gram, and the second); MKS is more common in engineering and CGS in physics. A number of other units have been defined by characteristic features or by historical practice; some that will be useful later are given in Table 2.2.

It's often more relevant to know the value on one quantity relative to another one, rather than the value itself. The ratio of two values $X_1$ and $X_2$, measured in *decibels* (*dB*), is defined to be

$$\mathrm{dB} = 20 \log_{10} \frac{X_1}{X_2} \quad . \tag{2.1}$$

If the *power* (energy per time) in two signals is $P_1$ and $P_2$, then

$$\mathrm{dB} = 10 \log_{10} \frac{P_1}{P_2} \quad . \tag{2.2}$$

This is because the power is the mean square amplitude (Chapter 3), and so to be consistent with equation (2.1) a factor of 2 is brought in to account for the exponent. An increase of 10 db therefore represents a increase by a factor of 10 in the relative power of two signals, or a factor of 3.2 in their values. A change of 3 dB in power is a change by a factor of 2.

The name decibel comes from Bell Labs. Engineers there working on the telephone system found it convenient to measure the gain or loss of devices on a logarithmic scale. Because the log of a product of two numbers is equal to the sum of their logs, this let them find the overall gain of a system by adding the logs of the components, and using logarithms also made it more convenient to express large numbers. They called the base-10 logarithm the *bel* in honor of Alexander Graham Bell; multiplying by 10 to bring up one more significant digit gave them a tenth-bel, or a decibel.

Some decibel reference levels occur so commonly that they are given names; popular ones include:

- *dBV* measures an electrical signal relative to 1 volt
- *dBm* measures relative to a 1 mW signal. The power will depend on the (usually unspecified) load, which traditionally is 50 Ω for radiofrequency signals and 600 Ω for audio ones (loads will be covered in Chapter 7). In audio recording, this is also called the *Volume Unit* or *VU*.
- *dBspl*, for *Sound Pressure Level* (or just *SPL*), measures sound pressure relative to a reference of $2\times10^{-5}$ Pa, the softest sound that the ear can perceive. The sound of a jet taking off is about 140 dBspl.

Finally, there are a number of fundamental observed constants in nature that we will use, shown in Table 2.3. In this list the digits in parentheses are the standard deviation uncertainty (see Chapter 3) in the corresponding digits, so that for example the error in the value for $G$ is $0.010\times10^{-11}$ (which, compared to the other constants, is an embarrasingly large uncertainty [Gundlach *et al.*, 1996]).

The speed of light no longer really belongs here, because its value has been defined exactly as part of the SI system. All the others are determined by exquisite metrology experiments. Each fundamental constant can appear in many different types of measurements, and these are done by many different groups, leading to multiple values that unfortunately don't always agree to within their careful error estimates. For this reason, the International Council of Scientific Unions in 1966 formed the *Committee on Data for Science and Technology* (*CODATA*) to do global optimizations over all these data to come up with an internally-consistent set of values; the most recent adjustment was done in 2006 [Mohr *et al.*, 2008].

Table 2.3. *Selected fundamental constants.*

| | | |
|---|---|---|
| gravitational constant ($G$) | = | $6.673(10)\times10^{-11}$ $\mathrm{m^3\cdot kg^{-1}\cdot s^{-2}}$ |
| speed of light ($c$) | = | $2.99792458\times10^{8}$ m/s |
| elementary charge ($e$) | = | $1.602176462(63)\times10^{-19}$ C |
| Boltzmann constant ($k$) | = | $1.3806503(24)\times10^{-23}$ J/K |
| Planck constant ($h$) | = | $6.62606876(52)\times10^{-34}$ $\mathrm{J\cdot s}$ |
| $\hbar = h/2\pi$ | = | $1.054571596(82)\times10^{-34}$ $\mathrm{J\cdot s}$ |
| Avogadro constant ($N_\mathrm{A}$) | = | $6.02214199(47)\times10^{23}$ $\mathrm{mol^{-1}}$ |
| electron mass ($m_e$) | = | $9.10938188(72)\times10^{-31}$ kg |
| proton mass ($m_p$) | = | $1.67262158(13)\times10^{-27}$ kg |
| gas constant ($R$) | = | $8.314472(15)$ $\mathrm{J\cdot mol^{-1}\cdot K^{-1}}$ |
| vacuum permittivity ($\epsilon_0$) | = | $10^7/(4\pi c^2) = 8.854188\ldots\times10^{-12}$ F/m |
| vacuum permeability ($\mu_0$) | = | $4\pi\times10^{-7}$ H/m |

## 2.2 PARTICLES AND FORCES

The world is built out of elementary particles and their interactions. There are a number of natural divisions in organization, energy, and length that occur between the structure of the nucleus of an atom and the structure of the universe; it will be useful to briefly survey this range in order to understand the relevant regimes for present and prospective information technologies.

This story starts with quantum mechanics, the laws that govern things that are very small. Around 1900 Max Planck was led by his inability to explain the spectrum of light from a hot oven to propose that the energy of light is quantized in units of $E = h\nu = hc/\lambda$, where $\nu$ is the frequency and $\lambda$ is the wavelength; $h = 6.626\ldots\times10^{-34}$ $\mathrm{J\cdot s}$ is now called *Planck's constant*. From there, in 1905 Einstein introduced the notion of massless photons as the discrete constituents of light, and in 1924 de Broglie suggested that the wavelength relationship applies to massive as well as massless particles by $\lambda = h/p$; $\lambda$ is the *de Broglie wavelength*, and is a consequence of the *wave–particle duality*: all quantum particles behave as both waves and particles. An electron, or a photon, can diffract like a wave from a periodic grating, but a detector will register the arrival of individual particles. Quantum effects usually become significant when the de Broglie wavelength becomes comparable to the size of an object.

Quantum mechanical particles can be either *fermions* (such as an electron) or *bosons* (such as a photon). Fermions and bosons are as unlike as anything can be in our universe. We will later see that bosons are particles that exist in states that are symmetric under the interchange of particles, they have an integer spin quantum number, and multiple bosons can be in the same quantum state. Fermions have half-integer spin, exist in states that are antisymmetric under particle interchange, and only one fermion can be in a particular quantum state. Spin is an abstract property of a quantum particle, but it behaves just like an angular momentum (as if the particle is spinning).

Particles can interact through four possible forces: *gravitational*, *electromagnetic*, *weak*, and *strong*. The first two are familiar because they have infinite range; the latter two operate on short ranges and are associated with nuclear and subnuclear processes (the characteristic lengths are approximately $10^{-15}$ m for the strong force and $10^{-18}$ m for the weak force). The electromagnetic force is so significant because of its strength: if a quantum atom was held together by gravitational forces alone (like a miniature solar system) its size would be on the order of $10^{23}$ m instead of $10^{-10}$ m. The macroscopic forces that we feel, such as the hardness of a wall, are transmitted to us by the electromagnetic force through the electrons in our atoms interacting with electrons in the adjoining atoms in the surface, but can be much more simply described in terms of fictitious effective forces ("the wall is hard").

All forces were originally thought to be transmitted by an intervening medium, the long-sought *ether* for electromagnetic forces. We now understand that forces operate by the exchange of spin-1 gauge bosons – the photon for the electromagnetic interaction (electric and magnetic fields), the $W^{\pm}$ and $Z^0$ bosons for the weak interaction, and eight gluons for the strong interaction (there is not yet a successful quantum theory of gravity). *Quantum ElectroDynamics* (*QED*) is the theory of the quantum electromagnetic interaction, and *Quantum ChromoDynamics* (*QCD*) the theory of the strong interaction. The weak and electromagnetic interactions are united in the *electroweak theory*, which, along with QCD is the basis for the *Standard Model*, the current summary of our understanding of particle physics. This amalgam of experimental observations and theoretical inferences successfully predicts most observed behavior extremely accurately, with two important catches: the theory has 20 or so adjustable parameters that must be determined from experiments, and it cannot explain gravitation. *String theory* [Giveon & Kutasov, 1999], a reformulation of particle theory that starts from loops rather than points as the primitive mathematical entity, appears to address both these limitations, and so is of intense interest in the theoretical physics community even though it is still far from being able to make experimentally testable predictions.

The most fundamental massive particles that we are aware of are the *quarks* and *leptons*. There's no reason to assume that there's nothing below them (i.e., turtles all the way down); there's just not a compelling reason right now to believe that there is. Quarks and leptons appear in the scattering experiments used to study particle physics to be point-particles without internal structure, and are spin-1/2 fermions. The leptons interact through the electromagnetic and weak interactions, and come in pairs: the *electron* and the electron *neutrino* ($e^-, \nu_e$), the *muon* and its neutrino ($\mu^-, \nu_\mu$), and the *tau lepton* and its neutrino ($\tau^-, \nu_\tau$). Muons and tau leptons are unstable, and therefore are seen only in accelerators, particle decay products, and cosmic rays. Because neutrinos interact only through the weak force, they can pass unhindered though a light-year of lead. But they are profoundly important for the energy balance of the universe, and if they have mass [Fukuda, 1998] it will have enormous implications for the fate of the universe. Quarks interact through the strong as well as weak and electromagnetic interactions, and they come in pairs: *up* and *down*, *charm* and *strange*, and *top* and *bottom*. These fanciful names are just labels for the underlying abstract states. The first member of each pair has charge +2/3, the second member has charge $-1/3$, and each charge flavor comes in three colors (once again, flavor and color are just descriptive names for quantum numbers).

Quarks combine to form *hadrons*; the best-known of which are the two *nucleons*. A proton comprises two ups and a down, and the neutron an up and two downs. The nucleons, along with their excited states, are called *baryons* and are fermions. Transitions between baryon states can absorb or emit spin-1 boson hadrons, called *mesons*. The size of hadrons is on the order of $10^{-15}$ m, and the energy difference between excited states is on the order of $10^9$ electron volts (1 GeV).

The nucleus of an atom is made up of some number of protons and neutrons, bound into ground and excited states by the strong interaction. Typical nuclear sizes are on the order of $10^{-14}$ m, and energies for nuclear excitations are on the order of $10^6$ eV (1 MeV). Atoms consist of a nucleus and electrons bound by the electromagnetic interaction; typical sizes are on the order of 1 ångstrom (Å, $10^{-10}$ m) and the energy difference between states is on the order of 1 eV. Notice the large difference in size between the atom and the nucleus: atoms are mostly empty space. Atoms can exist in different *isotopes* that have the same number of protons but differing numbers of neutrons, and *ions* are atoms that have had electrons removed or added.

Atoms can bond to form molecules; bond energies are on the order of 1 eV and bond lengths are on the order of 1 Å. Molecular sizes range from simple diatomic molecules up to enormous biological molecules with $10^6$–$10^9$ atoms. Large molecules fold into complex shapes; this is called their *tertiary structure*. These shapes are responsible for the geometrical constraints in molecular interactions that govern many biochemical pathways. Predicting tertiary structure is one of the most difficult challenges in chemistry.

Macroscopic materials are described by the arrangement of their constituent atoms, and include crystals (which have complete long-range ordering), liquids and glasses (which have short-range order but little long-range order), and gases (which have little short-range order). There are also very interesting intermediate cases, such as quasiperiodic alloys called *quasicrystals* that have deterministic translational order without translational periodicity [DiVincenzo & Steinhardt, 1991], and *liquid crystals* that maintain orientational but not translational ordering [Chandrasekhar, 1992]. Most solids do not contain just a single phase; there are usually defects and boundaries between different kinds of domains.

The atomic weight of an element is equal to the number of grams equal to one mole ($N_A \approx 10^{23}$) of atoms. It is approximately equal to the number of protons and neutrons in an atom, but differs because of the mix of naturally occuring isotopes. 22.4 liters of an ideal gas at a pressure of 1 atmosphere and at room temperature will also contain a mole of atoms.

The structure of a material at more fundamental levels will be invisible and can be ignored unless energies are larger than its characteristic excitations. Although we will rarely need to descend below atomic structure, there are a number of important applications of nuclear transitions, such as nuclear power and the use of nuclear probes to characterize materials.

## 2.3 ORDERS OF MAGNITUDE

Understanding what is possible and what is preposterous requires being familiar with the range of meaningful numbers for each unit; the following lists include some significant ones:

### *Time*

$10^{-43}$ s: the Planck time (Problem 2.7)

$10^{-15}$ s: this is the period of visible light, and a typical time scale for chemical reactions
$10^{-12}$ s: shortest logic gate delay
$10^{-9}$ s: atomic excitations and molecular rotations typically have lifetimes on the order of nanoseconds, and this is a characteristic computer clock cycle
$10^{-3}$ s: the shortest time difference that is consciously perceptible by people
$10^{17}$ s: the approximate age of the observable universe

### *Power and Energy*

1 eV: atomic excitations
$10^6$ eV: nuclear excitations
$10^9$ eV: subnuclear excitations
$10^{28}$ eV: the Planck energy
10 W: laptop computer
100 W: workstation; human
1000 W: house
$10^4$ W: car
$10^5$ W: building
$10^7$ W: supercomputer
$10^{26}$ W: luminosity of the sun
$10^{-12}$ W/m$^2$: softest sound that can be heard
1 W/m$^2$: loudest sound that can be tolerated
$10^7$ J/kg: energy density of food
$10^9$ J: energy in a ton of TNT
$10^{20}$ J: energy consumption in the US per year

### *Temperature*

$10^{-9}$ K: laser-cooled gas
2.75 K: microwave background radiation from the Big Bang
77 K: liquid nitrogen
300 K: room temperature
6000 K: surface of the sun

### *Mass*

$10^{-27}$ kg: proton mass
$10^{-12}$ kg: typical cell
$10^{-5}$ kg: small insect
$10^{16}$ kg: Earth's biomass
$5.98\times10^{24}$ kg: the mass of the Earth
$10^{42}$ kg: approximate mass of the Milky Way

### *Length*

$10^{-35}$ m: the Planck distance
$10^{-15}$ m: size of a proton

$10^{-10}$ m: size of an atom
$4\times10^5$ m: height of a Low Earth Orbit satellite above the surface
$6.378\times10^6$ m: radius of the Earth
$4\times10^7$ m: height of a geosynchronous satellite above the equator
$10^{11}$ m: distance from the Earth to the Sun
$10^{20}$ m: Milky Way radius
$10^{26}$ m: size of the observable universe

### *Electromagnetic spectrum*

$< 0.1$ Å: gamma rays
0.1–100 Å: X-rays
100–4000 Å: UV (atomic ionization energy)
4000–7000 Å: visible (this coincides with a transmission band through the atmosphere, and corresponds to $10^{14}$–$10^{15}$ Hz)
0.7–100 μm: IR (thermal radiation)
0.01–10 cm: microwave (GHz)
0.1–$10^3$ m: radio (MHz–kHz)

### *Magnetic and Electric Fields*

$10^{-12}$ tesla: magnetic field needed for radio reception
$10^{-6}$ tesla: magnetic field generated by a cordless phone
$3\times10^{-5}$ tesla: magnetic field at the Earth's surface
20 tesla: large superconducting/normal hybrid magnet
$10^4$ A: lightning bolt current
$10^8$ V: potential across a lightning bolt
$3\times10^6$ V/m: breakdown voltage in air

### *Number*

$10^5$: number of DNA bases in a bacteriophage
$4\times10^6$: bytes in the Bible
$10^9$: number of DNA bases in a mammal
$10^{13}$: number of synapses in the human cortex
$10^{14}$: bytes passing through the Internet backbone during December, 1994
$10^{80}$: approximate number of atoms in the universe

## 2.4 SELECTED REFERENCES

[Cohen *et al*., 2003] Cohen, E. Richard, Lide, David R., & Trigg, George L. (eds). (2003). *A Physicist's Desk Reference*. New York: Springer.

This is a handy summary of units, conversion factors, and governing equations.

[Lerner & Trigg, 2005] Lerner, Rita G., & Trigg, George L. (eds). (2005). *Encyclopedia of Physics*. 3rd edn. New York: Wiley.

A Who's Who of interesting physical phenomena.

[Morrison & Morrison, 1982] Morrison, Philip, & Morrison, Phylis. (1982). *Powers Of Ten: A Book About the Relative Size of Things*. Redding: Scientific American Library.

The Morrisons provide a marvelous tour through the characteristic phenomena at many length scales.

[Nachtmann, 1990] Nachtmann, Otto. (1990). *Elementary Particle Physics: Concepts and Phenomena*. New York: Springer-Verlag. Translated by A. Lahee and W. Wetzel.

A nice introduction to particles and forces.

## 2.5 PROBLEMS

(2.1) (*a*) How many atoms are there in a yoctomole?

(*b*) How many seconds are there in a nanocentury? Is the value near that of any important constants?

(2.2) A large data storage system holds on the order of a petabyte. How tall would a 1 petabyte stack of CDs be? How does that compare to the height of a tall building?

(2.3) If all the atoms in our universe were used to write an enormous binary number, using one atom per bit, what would that number be (converted to base 10)?

(2.4) Compare the gravitational acceleration due to the mass of the Earth at its surface to that produced by a 1 kg mass at a distance of 1 m. Express their ratio in decibels.

(2.5) (*a*) Approximately estimate the chemical energy in a ton of TNT. You can assume that nitrogen is the primary component; think about what kind of energy is released in a chemical reaction, where it is stored, and how much there is.

(*b*) Estimate how much uranium would be needed to make a nuclear explosion equal to the energy in a chemical explosion in 10 000 tons of TNT (once again, think about where the energy is stored).

(*c*) Compare this to the *rest mass energy* $E = mc^2$ of that amount of material (Chapter 15), which gives the maximum amount of energy that could be liberated from it.

(2.6) (*a*) What is the approximate de Broglie wavelength of a thrown baseball?

(*b*) Of a molecule of nitrogen gas at room temperature and pressure? (This requires either the result of Section 3.4.2, or dimensional analysis.)

(*c*) What is the typical distance between the molecules in this gas?

(*d*) If the volume of the gas is kept constant as it is cooled, at what temperature does the wavelength become comparable to the distance between the molecules?

(2.7) (*a*) The potential energy of a mass $m$ a distance $r$ from a mass $M$ is $-GMm/r$. What is the *escape velocity* required to climb out of that potential?

(*b*) Since nothing can travel faster than the speed of light (Chapter 15), what is the radius within which nothing can escape from the mass?

(*c*) If the rest energy of a mass $M$ is converted into a photon, what is its wavelength?

(*d*) For what mass does its equivalent wavelength equal the size within which light cannot escape?

(*e*) What is the corresponding size?

(*f*) What is the energy?

(*g*) What is the period?

(2.8) Consider a pyramid of height $H$ and a square base of side length $L$. A sphere is placed so that its center is at the center of the square at the base of the pyramid, and so that it is tangent to all of the edges of the pyramid (intersecting each edge at just one point).

(*a*) How high is the pyramid in terms of $L$?

(*b*) What is the volume of the space common to the sphere and the pyramid?

(This question comes from an entrance examination for humanities students at Tokyo University [*Economist*, 1993].)

# Bibliography

[Abrams & Lloyd, 1998] Abrams, D.S., & Lloyd, S. (1998). Nonlinear Quantum Mechanics Implies Polynomial-Time Solution for NP-Complete and P Problems. *Physical Review Letters*, **81**, 3992–5.

[Adleman, 1994] Adleman, L.M. (1994). Molecular Computation of Solutions to Combinatorial Problems. *Science*, **266**, 1021–3.

[Aharonov & Bohm, 1961] Aharonov, Y., & Bohm, D. (1961). Time in the Quantum Theory and the Uncertainty Relation for Time and Energy. *Physical Review*, **122**, 1649–1658.

[Alt & Pleshko, 1974] Alt, P.M., & Pleshko, P. (1974). Scanning Limitations of Liquid-Crystal Displays. *IEEE Transactions on Electron Devices*, **ED-21**, 146–55.

[Alvelda & Lewis, 1998] Alvelda, P., & Lewis, N.D. (1998). New Ultra-Portable Display Technology and Applications. *Proceedings of SPIE*, **3362**, 322–5.

[Anderson, 1992] Anderson, J.L. (1992). Why We Use Retarded Potentials. *American Journal of Physics*, **60**, 465–7.

[Anderson *et al.*, 1995] Anderson, M.H., Ensher, J.R., Matthews, M.R., Wieman, C.E., & Cornell, E.A. (1995). Observation of Bose–Einstein Condensation in a Dilute Atomic Vapor. *Science*, **269**, 198–201.

[Ash, 1990] Ash, Robert B. (1990). *Information Theory*. New York: Dover Publications.

[Ashcroft & Mermin, 1976] Ashcroft, N., & Mermin, N.D. (1976). *Solid State Physics*. New York: Holt, Rinehart and Winston.

[Aspect *et al.*, 1981] Aspect, A., Grangier, P., & Roger, G. (1981). Experimental Tests of Realistic Local Theories via Bell's Theorem. *Physical Review Letters*, **47**, 460–3.

[Athas *et al.*, 1994] Athas, W.C., Svensson, L.J., Koller, J.G., Tzartzanis, N., & Chou, E. Ying-Chin. (1994). Low-Power Digital Systems Based on Adiabatic-Switching Principles. *IEEE Transactions on VLSI Systems*, **2**, 398–407.

[Awschalom & Flatté, 2007] Awschalom, David D., & Flatté, Michael E. (2007). Challenges for Semiconductor Spintronics. *Nature Physics*, **3**, 153–159.

[Baibich *et al.*, 1988] Baibich, M.N., Broto, J.M, Fert, A., Dau, F. Nguyen Van, Petroff, F., Etienne, P., Creuzet, G., Friederich, A., & Chazelas, J. (1988). Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices. *Physical Review Letters*, **61**, 2472–5.

[Balanis, 1997] Balanis, Constantine. (1997). *Antenna Theory: Analysis and Design*. 2nd edn. New York: Wiley.

[Balian, 1991] Balian, Roger. (1991). *From Microphysics to Macrophysics: Methods and Applications of Statistical Physics*. New York: Springer–Verlag. Translated by D. ter Haar and J.F. Gregg, 2 volumes.

[Bardeen *et al.*, 1957] Bardeen, J., Cooper, L.N., & Schrieffer, J.R. (1957). Theory of Superconductivity. *Physical Review*, **108**, 1175–1204.

[Barenco *et al.*, 1995] Barenco, Adriano, Bennett, Charles H., Cleve, Richard, DiVincenzo, David P., Margolus, Norman, Shor, Peter, Sleator, Tycho, Smolin, John, & Weinfurter, Harald. (1995). Elementary Gates for Quantum Computation. *Phys. Rev. A*, **52**, 3457–67.

[Baym, 1973] Baym, Gordon. (1973). *Lectures on Quantum Mechanics*. Reading: W.A. Benjamin.

[Beckman *et al*., 1996] Beckman, D., Chari, A.N., Devabhaktuni, S., & Preskill, J. (1996). Efficient Networks for Quantum Factoring. *Physical Review A*, **54**, 1034–63.

[Bell, 1964] Bell, J. (1964). On The Einstein Podolsky Rosen Paradox. *Physics*, **1**, 195–200.

[Benioff, 1980] Benioff, P. (1980). The Computer as a Physical System: A Microscopic Quantum Mechanical Hamiltonian Model of Computers as Represented by Turing Machines. *Journal of Statistical Physics*, **22**, 563–91.

[Bennett, 1973] Bennett, C.H. (1973). Logical Reversibility of Computation. *IBM Journal of Research and Development*, **17**, 525.

[Bennett, 1988] Bennett, C.H. (1988). Notes on the History of Reversible Computation. *IBM Journal of Research and Development*, **32**, 16–23.

[Bennett & Brassard, 1984] Bennett, C.H., & Brassard, G. (1984). Quantum Cryptography: Public Key Distribution and Coin Tossing. Pages 175–9 of: *Proceedings of IEEE International Conference on Computers, Systems, and Signal Processing*. New York: IEEE.

[Bennett & Brassard, 1989] Bennett, C.H., & Brassard, G. (1989). The Dawn of a New Era for Quantum Cryptography: the Experimental Prototype is Working. *Sigact News*, **20**, 78–82.

[Bennett *et al*., 1993] Bennett, C.H., Brassard, G., Crepeau, C., Jozsa, R., & Wootters, A. Peres W.K. (1993). Teleporting an Unknown Quantum State via Dual Classical and Einstein–Podolsky–Rosen channels. *Physical Review Letters*, **70**, 1895–9.

[Benton, 1969] Benton, S.A. (1969). Hologram Reconstructions With Extended Incoherent Sources. *Journal of the Optical Society of America*, **59**, 1545–6.

[Berggren *et al*., 2007] Berggren, M., Nilsson, D., & Robinson, N.D. (2007). Organic Materials for Printed Electronics. *Nature Materials*, **6**, 3–5.

[Berry & Geim, 1997] Berry, M.V., & Geim, A.K. (1997). Of Flying Frogs and Levitrons Magnetic Levitation. *European Journal of Physics*, **18**, 307–13.

[Bertram *et al*., 1998] Bertram, H.N., Zhou, H., & Gustafson, R. (1998). Signal to Noise Ratio Scaling and Density Limit Estimates in Longitudinal Magnetic Recording. *IEEE Transactions on Magnetics*, **34**, 1845–7.

[Besag *et al*., 1995] Besag, J., Green, P.J., Higdon, D., & Mengersen, K. (1995). Bayesian Computation and Stochastic Systems. *Statistical Science*, **10**, 3–66.

[Bhaskar *et al*., 1996] Bhaskar, N.D., White, J., Mallette, L.A., McClelland, T.A., & Hardy, J. (1996). A Historical Review of Atomic Frequency Standards used in Space Systems. Pages 24–32 of: *Proceedings of the 1996 IEEE International Frequency Control Symposium*. New York: IEEE.

[Binnig *et al*., 1986] Binnig, G., Quate, C.F., & Gerber, C. (1986). Atomic Force Microscope. *Physical Review Letters*, **56**, 930–3.

[BIPM, 1998] BIPM. (1998). *The International System of Units (SI)*. Organisation Intergouvernementale de la Convention du Métre.

[Birtwistle & Davis, 1995] Birtwistle, G., & Davis, A. (eds). (1995). *Asynchronous Digital Circuit Design*. New York: Springer-Verlag.

[Bitzer, 1999] Bitzer, D.L. (1999). Inventing the AC Plasma Panel. *Information Display*, **15**, 22–7.

[Black, 1934] Black, H.S. (1934). Stabilized Feedback Amplifiers. *Bell System Technical Journal*, **13**, 1–18.

[Blahut, 1988] Blahut, Richard E. (1988). *Principles and Practice of Information Theory*. Reading: Addison-Wesley.

[Boguna & Corral, 1997] Boguna, M., & Corral, A. (1997). Long-Tailed Trapping Times and Levy Flights in a Self-Organized Critical Granular System. *Physical Review Letters*, **78**, 4950–3.

[Born & Wolf, 1999] Born, Max, & Wolf, Emil. (1999). *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*. 7th edn. Cambridge: Cambridge University Press.

[Bortoletto *et al*., 1999] Bortoletto, F., Bonoli, C., Fantinel, D., Gardio, D., & Pernechele, C. (1999). An Active Telescope Secondary Mirror Control System. *Review of Scientific Instruments*, **70**, 2856–60.

[Bove, 1998] Bove, V.M. (1998). Object-Based Media and Stream-Based Computing. *Proceedings of SPIE*, **3311**, 24–9.

[Boyer *et al*., 1998] Boyer, M., Brassard, G., Hoyer, P., & Tapp, A. (1998). Tight Bounds on Quantum Searching. *Progress of Physics*, **46**, 493–505.

[Boyle & Smith, 1971] Boyle, W.S., & Smith, G.E. (1971). Charge-Coupled Devices – A New Approach to MIS Device Structures. *IEEE Spectrum*, **8**, 18–27.

[Brodie & Muray, 1982] Brodie, Ivor, & Muray, Julius J. (1982). *The Physics of Microfabrication.* New York: Plenum Press.

[Brody, 1996] Brody, T.P. (1996). The Birth and Early Childhood of Active Matrix – A Personal Memoir. *Journal of the Society for Information Display*, **4**, 113–27.

[Brunel *et al*., 1999] Brunel, C., Lounis, B., Tamarat, P., & Orrit, M. (1999). Triggered Source of Single photons based on Controlled Single Molecule Fluorescence. *Physical Review Letters*, **83**, 2722–5.

[Brush, 1976] Brush, Stephen G. (1976). *The Kind of Motion We Call Heat: A History of the Kinetic Theory of Gases in the 19th Century*. New York: North-Holland. 2 volumes.

[Buschow, 1991] Buschow, K.H.J. (1991). New Developments in Hard Magnetic Materials. *Reports on Progress in Physics*, **54**, 1123–213.

[Calderbank & Shor, 1996] Calderbank, A.R., & Shor, P.W. (1996). Good Quantum Error-Correcting Codes Exist. *Physical Review A*, **54**, 1098–105.

[Callen, 1985] Callen, Herbert B. (1985). *Thermodynamics and an Introduction to Thermostatistics*. 2nd edn. New York: Wiley.

[Campbell & Green, 1966] Campbell, F.W., & Green, D. (1966). Optical and Retinal Factors Affecting Visual Resolution. *Journal of Physiology*, **181**, 576–93.

[Chandrasekhar, 1992] Chandrasekhar, S. (1992). *Liquid Crystals*. 2nd edn. Cambridge: Cambridge University Press.

[Chapin *et al*., 1954] Chapin, D.M., Fuller, C.S., & Pearson, G.L. (1954). A New Silicon *p–n* Junction Photocell for Converting Solar Radiation into Electrical Power. *Journal of Applied Physics*, **25**, 676.

[Chen *et al*., 1996] Chen, R. H., Korotkov, A. N., & Likharev, K. K. (1996). Single-Electron Transistor Logic. *Appl. Phys. Lett*., **68**, 1954–1956.

[Choma *et al*., 2003] Choma, Michael A., Sarunic, Marinko V., Yang, Changhuei, & Izatt, Joseph A. (2003). Sensitivity advantage of swept source and Fourier domain optical coherence tomography. *Optics Express*, **11**, 2183–2189.

[Chow *et al*., 1985] Chow, W.W., Gea-Banacloche, J., Pedrotti, L.M., Sanders, V.E., Schleich, W., & Scully, M.O. (1985). The Ring Laser Gyro. *Reviews of Modern Physics*, **57**, 61–104.

[Chu & Wong, 1982] Chu, S., & Wong, S. (1982). Linear Pulse Propagation in an Absorbing Medium. *Physical Review Letters*, **48**, 738–741.

[Chuang *et al*., 1998a] Chuang, I.L., Gershenfeld, N., Kubinec, M.G., & Leung, D.W. (1998a). Bulk Quantum Computation with Nuclear Magnetic Resonance: Theory and Experiment. *Proceedings of the Royal Society of London Series A*, **454**, 447–67.

[Chuang *et al*., 1998b] Chuang, I.L., Gershenfeld, N., & Kubinec, M. (1998b). Experimental Implementation of Fast Quantum Searching. *Physical Review Letters*, **80**, 3408–11.

[Cirac & Zoller, 1995] Cirac, J.I., & Zoller, P. (1995). Quantum Computations with Cold Trapped Ions. *Physical Review Letters*, **74**, 4091–4.

[Clarke, 1999] Clarke, R.J. (1999). Image and Video Compression: A Survey. *International Journal of Imaging Systems & Technology*, **10**, 20–32.

[Cohen *et al.*, 2003] Cohen, E. Richard, Lide, David R., & Trigg, George L. (eds). (2003). *A Physicist's Desk Reference*. New York: Springer.

[Comiskey *et al.*, 1998] Comiskey, B., Albert, J.D., Yoshizawa, H., & Jacobson, J. (1998). An Electrophoretic Ink for All-Printed Reflective Electronic Displays. *Nature*, **394**, 253–5.

[Conway, 1991] Conway, B.E. (1991). Transition from Supercapacitor to Battery Behavior in Electrochemical Energy-Storage. *Journal of the Electrochemical Society*, **138**, 1539–48.

[Conway & Sloane, 1993] Conway, J.H., & Sloane, N.J.A. (1993). *Sphere Packings, Lattices, and Groups*. 2nd edn. New York: Springer-Verlag.

[Cook, 1971] Cook, S.A. (1971). The Complexity of Theorem-Proving Procedures. Pages 151–8 of: *Proceedings of the 3rd Annual ACM Symposium on the Theory of Computing*. New York: Association for Computing Machinery.

[Cooper *et al.*, 1999] Cooper, E.B., Manalis, S.R., Fang, H., Dai, H., Matsumoto, K., Minne, S.C., Hunt, T., & Quate, C.F. (1999). Terabit-per-Square-Inch Data Storage with the Atomic Force Microscope. *Applied Physics Letters*, **75**, 3566–8.

[Cooper, 1956] Cooper, L.N. (1956). *Physical Review*, **104**, 1189.

[Corney, 1978] Corney, Alan. (1978). *Atomic and Laser Spectroscopy*. Oxford: Clarendon Press.

[Cory *et al.*, 1997] Cory, D.G., Fahmy, A.F., & Havel, T.F. (1997). Ensemble Quantum Computing by NMR Spectroscopy. *Proceedings of the National Academy of Science*, **94**, 1634–9.

[Cory *et al.*, 1998] Cory, D.G., Price, M.D., Maas, W., Knill, E., Laflamme, R., Zurek, W.H., Havel, T.F., & Somaroo, S.S. (1998). Experimental Quantum Error Correction. *Physical Review Letters*, **81**, 2152–5.

[Cover & Thomas, 1991] Cover, Thomas M., & Thomas, Joy A. (1991). *Elements of Information Theory*. New York: Wiley.

[Cowper, 1998] Cowper, R. (1998). A View of Next Generation Optical Communication Systems – Possible Future High-Capacity Transport Implementations. *Proceedings of SPIE*, **3491**, 575–80.

[Crisanti *et al.*, 1993] Crisanti, A., Jensen, M.H., Vulpiani, A., & Paladin, G. (1993). Intermittency and Predictability in Turbulence. *Physical Review Letters*, **70**, 166–9.

[Crommie *et al.*, 1993] Crommie, M.F., Lutz, C.P., & Eigler, D.M. (1993). Confinement of Electrons to Quantum Corrals on a Metal Surface. *Science*, **262**, 218–20.

[Danzer, 1999] Danzer, Paul (ed). (1999). *The ARRL Handbook for Radio Amateurs*. 76th edn. Newington: American Radio Relay League.

[Datta & Das, 1990] Datta, Supriyo, & Das, Biswajit. (1990). Electronic Analog of the ElectroOptic Modulator. *Appl. Phys. Lett.*, **56**, 665–667.

[Davis *et al.*, 1977] Davis, J.R., Dinger, R.J., & Goldstein, J.A. (1977). Development of a Superconducting ELF Receiving Antenna. *IEEE Transactions on Antennas & Propagation*, **AP-25**, 223–31.

[de Groot & Mazur, 1984] de Groot, S.R., & Mazur, P. (1984). *Non-Equilibrium Thermodynamics*. Mineola: Dover Publications, Inc.

[Delavaux & Nagel, 1995] Delavaux, J.-M.P., & Nagel, J.A. (1995). Multi-Stage Erbium-Doped Fiber Amplifier Designs. *Journal of Lightwave Technology*, **13**, 703–20.

[Denk *et al.*, 1990] Denk, W., Strickler, J.H., & Webb, W.W. (1990). Two-Photon Laser Scanning Fluorescence Microscopy. *Science*, **248**, 73–6.

[Dennard, 1968] Dennard, R.H. (1968). *Field-Effect Transistor Memory*. US Patent No. 3 387 286.
[Denyer *et al*., 1995] Denyer, P.B., Renshaw, D., & Smith, S.G. (1995). Intelligent CMOS Imaging. *Proceedings of SPIE*, **2415**, 285–91.
[Deutsch, 1985] Deutsch, D. (1985). Quantum Theory, the Church–Turing Principle and the Universal Quantum Computer. *Proceedings of the Royal Society of London Series A*, **A400**, 97–117.
[Dickinson & Denker, 1995] Dickinson, A.G., & Denker, J.S. (1995). Adiabatic Dynamic Logic. *IEEE Journal of Solid-State Circuits*, **30**, 311–5.
[Dieny *et al*., 1991] Dieny, B., Speriosu, V.S., Parkin, S.S.P., Gurney, B.A., Wilhoit, D.R., & Mauri, D. (1991). Giant Magnetoresistive in Soft Ferromagnetic Multilayers. *Phys. Rev. B*, **43**, 1297–1300.
[Diffie & Hellman, 1976] Diffie, W., & Hellman, M. (1976). New Directions in Cryptography. *IEEE Transactions on Information Theory*, **IT-22**, 644–54.
[DiVincenzo & Steinhardt, 1991] DiVincenzo, David P., & Steinhardt, Paul J. (eds). (1991). *Quasicrystals: The State of the Art*. Singapore: World Scientific.
[Dixon, 1984] Dixon, R.C. (1984). *Spread Spectrum Systems*. New York: John Wiley & Sons.
[Dolling *et al*., 2006] Dolling, Gunnar, Enkrich, Christian, Wegener, Martin, Soukoulis, Costas M., & Linden, Stefan. (2006). Simultaneous Negative Phase and Group Velocity of Light in a Metamaterial. *Science*, **312**, 892–894.
[Drexler, 1992] Drexler, K. Eric. (1992). *Nanosystems: Molecular Machinery, Manufacturing, and Computation*. New York: John Wiley & Sons.
[Durrani *et al*., 1999] Durrani, Z.A.K., Irvine, A.C., Ahmed, H., & Nakazato, K. (1999). A Memory Cell with Single-Electron and Metal-Oxide-Semiconductor Transistor Integration. *Applied Physics Letters*, **74**, 1293–5.
[Dutta & Horn, 1981] Dutta, P., & Horn, P.M. (1981). Low-Frequency Fluctuations in Solids: $1/f$ Noise. *Reviews of Modern Physics*, **53**, 497–516.
[*Economist*, 1993] *Economist*. (1993). **326**, 49 (January 30th).
[Edelstein *et al*., 1997] Edelstein, D., Heidenreich, J., Goldblatt, R., Cote, W., Uzoh, C., Lustig, N., Roper, P., McDevitt, T., Motsiff, W., Simon, A., Dukovic, J., Wachnik, R., Rathore, H., Schulz, R., Su, L., Luce, S., & Slattery, J. (1997). Full Copper Wiring in a Sub-0.25 $\mu$m CMOS ULSI Technology. Pages 773–776 of: *Proceedings of the IEEE International Electron Devices Meeting*. New York: IEEE.
[Einstein, 1905] Einstein, A. (1905). Zur Electrodynamik bewegter Körper. *Annalen der Physik*, **17**, 891–921.
[Einstein, 1916] Einstein, A. (1916). Grundlagen der allgemeinen Relativitätstheorie. *Annalen der Physik*, **49**, 769–822.
[Einstein *et al*., 1935] Einstein, A., Podolsky, B., & Rosen, N. (1935). Can Quantum-Mechanical Description of Physical Reality be Considered Complete? *Physical Review*, **47**, 777–80.
[Ekert & Jozsa, 1996] Ekert, Artur, & Jozsa, Richard. (1996). Quantum Computation and Shor's Factoring Algorithm. *Reviews of Modern Physics*, **68**(3), 733–53.
[Ernst *et al*., 1994] Ernst, R.R., Bodenhausen, G., & Wokaun, A. (1994). *Principles of Nuclear Magnetic Resonance in One and Two Dimensions*. Oxford: Oxford University Press.
[Everett, 1957] Everett, Hugh. (1957). Relative State Formulation of Quantum Mechanics. *Reviews of Modern Physics*, **29**, 454–62.
[Farhi *et al*., 1998] Farhi, E., Goldstone, J., Gutmann, S., & Sipser, M. (1998). Limit on the Speed of Quantum Computation in Determining Parity. *Physical Review Letters*, **81**, 5442–4.
[Fauchet, 1998] Fauchet, P.M. (1998). Progress Toward Nanoscale Silicon Light Emitters. *IEEE Journal of Selected Topics in Quantum Electronics*, **4**, 1020–8.

[Feller, 1968] Feller, William. (1968). *An Introduction to Probability Theory and Its Applications*. 3rd edn. New York: Wiley.

[Feller, 1974] Feller, William. (1974). *An Introduction to Probability Theory and Its Applications*. 2nd edn. Vol. II. New York: Wiley.

[Fercher *et al*., 2003] Fercher, A.F., Drexler, W., Hitzenberger, C.K., & Lasser, T. (2003). Optical Coherence Tomography–Principles and Applications. *Rep. Prog. Phys.*, **66**, 239–303.

[Fergason, 1985] Fergason, J.L. (1985). Polymer Encapsulated Nematic Liquid Crystals for Display and Light Control Applications. Pages 68–70 of: *1985 SID International Symposium*. New York: Pallisades Institute for Research Services.

[Feynman, 1982] Feynman, R.P. (1982). Simulating Physics with Computers. *International Journal of Theoretical Physics*, **21**, 467–88.

[Feynman, 1992] Feynman, R.P. (1992). There's Plenty of Room at the Bottom (Data Storage). *Journal of Microelectromechanical Systems*, **1**, 60–6.

[Fink *et al*., 1998] Fink, Y., Winn, J.N., Shanhui, Fan, Chiping, Chen, Michel, J., Joannopoulos, J.D., & Thomas, E.L. (1998). A Dielectric Omnidirectional Reflector. *Science*, **282**, 1679–82.

[Fischer *et al*., 1972] Fischer, A.G., Brody, T.P., & Escott, W.S. (1972). Design of a Liquid Crystal Color TV Panel. Pages 64–6 of: *Conference on Display Devices*. IEEE Conference Record of 1972. Piscataway: IEEE.

[Fitch, 1988] Fitch, J. Patrick. (1988). *Synthetic Aperture Radar*. New York: Springer-Verlag.

[Fleischhauer *et al*., 2005] Fleischhauer, Michael, Imamoglu, Atac, & Marangos, Jonathan P. (2005). Electromagnetically Induced Transparency: Optics in Coherent Media. *Reviews of Modern Physics*, **77**, 633–673.

[Fletcher *et al*., 1997] Fletcher, R., Levitan, J.A., Rosenberg, J., & Gershenfeld, N. (1997). Application of Smart Materials to Wireless ID Tags and Remote Sensors. George, E.P., Gotthardt, R., Otsuka, K., Trolier-McKinstry, S., & Wun-Fogle, M. (eds), *Materials for Smart Systems II*. Pittsburgh: Materials Research Society.

[Fletcher *et al*., 1993] Fletcher, R.M., Kuo, K. Chihping, Osentowski, T.D., Jiann, G.Y., & Robbins, V.M. (1993). High-Efficiency Aluminum Indium Gallium Phosphide Light-Emitting Diodes. *Hewlett-Packard Journal*, **44**, 6–14.

[Fowler & Nordheim, 1928] Fowler, R.H., & Nordheim, L. (1928). Electron Emission in Intense Electric Fields. *Proceedings of the Royal Society of London*, **119**, 173–81.

[Fox *et al*., 2001] Fox, G.R., Chu, F., & Davenport, T. (2001). Current and Future Ferroelectric Nonvolatile Memory Technology. *J. Vac. Sci. Technol. B*, **19**, 1967–1971.

[Fraden, 1993] Fraden, Jacob. (1993). *AIP Handbook of Modern Sensors: Physics, Designs and Applications*. New York: American Institute of Physics.

[Friend *et al*., 1999] Friend, R.H., Gymer, R.W., Holmes, A.B., Burroughes, J.H., Marks, R.N., Taliani, C., Bradley, D.D.C, Santos, D.A. Dos, Bredas, J.L., Logdlund, M., & Salaneck, W.R. (1999). Electroluminescence in Conjugated Polymers. *Nature*, **397**, 121–8.

[Fujimoto, 2001] Fujimoto, James G. (2001). Optical coherence tomography. *Comptes Rendus de lÅAcadémie des Sciences - Series IV - Physics*, **2**, 1099–1111.

[Fukada & Yasuda, 1957] Fukada, E., & Yasuda, L. (1957). On the Piezoelectric Effect of Bone. *Journal of the Physical Society of Japan*, **12**, 1158.

[Fukuda, 1998] Fukuda, Y. (1998). Evidence for Oscillation of Atmospheric Neutrinos. *Physical Review Letters*, **81**, 1562–7.

[Fukushima & Roeder, 1981] Fukushima, Eiichi, & Roeder, Stephen B.W. (1981).

*Experimental Pulse NMR: A Nuts and Bolts Approach*. Reading: Addison-Wesley.

[Furusawa *et al*., 1998] Furusawa, A., Sorensen, J.L., Braunstein, S.L., Fuchs, C.A., Kimble, H.J., & Polzik, E.S. (1998). Unconditional Quantum Teleportation. *Science*, **282**, 706–9.

[Gabor, 1948] Gabor, D. (1948). A New Microscopic Principle. *Nature*, **161**, 777–8.

[Gabor, 1966] Gabor, D. (1966). Holography of the "Whole Picture". *New Scientist*, **29**, 74–8.

[Galtarossa *et al*., 1994] Galtarossa, A., Someda, C.G., Matera, F., & Schiano, M. (1994). Polarization Mode Dispersion in Long Single-Mode-Fiber Links: A Review. *Fiber & Integrated Optics*, **13**, 215–29.

[Garey & Johnson, 1979] Garey, Michael R., & Johnson, David S. (1979). *Computers and Intractability: A Guide to the Theory of NP-completeness*. San Francisco: W.H. Freeman.

[Garrett & McCumber, 1970] Garrett, C.G.B., & McCumber, D.E. (1970). Propagation of Gaussian Light Pulse through an Anomalous Dispersion Medium. *Physical Review A*, **1**, 305–313.

[Geim & Novoselov, 2007] Geim, A.K., & Novoselov, K.S. (2007). The Rise of Graphene. *Nature Materials*, **6**, 183–191.

[Gershenfeld, 1993] Gershenfeld, N.A. (1993). Information in Dynamics. Pages 276–80 of: Matzke, Doug (ed), *Proceedings of the Workshop on Physics of Computation*. Piscataway: IEEE Press.

[Gershenfeld, 1996] Gershenfeld, N.A. (1996). Signal Entropy and the Thermodynamics of Computation. *IBM Systems Journal*, **35**, 577–86.

[Gershenfeld, 1999a] Gershenfeld, N.A. (1999a). *The Nature of Mathematical Modeling*. Cambridge: Cambridge University Press.

[Gershenfeld, 1999b] Gershenfeld, N.A. (1999b). *When Things Start To Think*. New York: Henry Holt and Company.

[Gershenfeld & Chuang, 1997] Gershenfeld, N.A., & Chuang, I.L. (1997). Bulk Spin Resonance Quantum Computation. *Science*, **275**, 350–6.

[Gershenfeld & Grinstein, 1995] Gershenfeld, N.A., & Grinstein, G. (1995). Entrainment and Communication with Dissipative Pseudorandom Dynamics. *Physical Review Letters*, **74**, 5024–7.

[Gershenfeld *et al*., 2010] Gershenfeld, Neil, Dalrymple, David, Chen, Kailiang, Knaian, Ara, Green, Forrest, Demaine, Erik D., Greenwald, Scott, & Schmidt-Nielsen, Peter. (2010). Reconfigurable asynchronous logic automata: (RALA). *SIGPLAN Not*., **45**, 1–6.

[Ghrayeb *et al*., 1997] Ghrayeb, J., Jackson, T.W., Daniels, R., & Hopper, D.G. (1997). Review of Field Emission Display Potential as a Future (Leap-Frog) Flat Panel Technology. *Proceedings of SPIE*, **3057**, 237–48.

[Gibble & Chu, 1993] Gibble, K., & Chu, S. (1993). Laser-Cooled Cs Frequency Standard and a Measurement of the Frequency Shift due to Ultracold Collisions. *Physical Review Letters*, **70**, 1771–4.

[Gilbert, 1975] Gilbert, B. (1975). A New Technique for Analog Multiplication. *IEEE Journal of Solid-State Circuits*, **SC-10**, 437–47.

[Ginger *et al*., 2004] Ginger, David S., Zhang, Hua, & Mirkin, Chad A. (2004). The Evolution of Dip-Pen Nanolithography. *Angew. Chem. Int. Ed*.

[Ginzburg & Landau, 1950] Ginzburg, V.L., & Landau, L.D. (1950). Concerning the Theory of Superconductivity. *Soviet Physics JETP*, **20**, 1064–82.

[Girard, 1994] Girard, G. (1994). The Third Periodic Verification of National Prototypes of the Kilogram (1988–1992). *Metrologia*, **31**, 317–36.

[Giveon & Kutasov, 1999] Giveon, A., & Kutasov, D. (1999). Brane Dynamics and Gauge Theory. *Reviews of Modern Physics*, **71**, 983–1084.

[Goldstein, 1980] Goldstein, Herbert. (1980). *Classical Mechanics*. 2nd edn. Reading: Addison-Wesley.

[Grabert & Devoret, 1992] Grabert, Hermann, & Devoret, Michel H. (eds). (1992). *Single Charge Tunneling: Coulomb Blockade Phenomena in Nanostructures*. New York: Plenum Press.

[Greenberger *et al*., 1990] Greenberger, D.M., Horne, M.A., Shimony, A., & Zeilinger, A. (1990). Bell's Theorem Without Inequalities. *American Journal of Physics*, **58**, 1131–43.

[Grochowski *et al*., 1993] Grochowski, E.G., Hoyt, R.F., & Heath, J.S. (1993). Magnetic Hard Disk Drive Form Factor Evolution. *IEEE Transactions on Magnetics*, **29**, 4065–7. Part 2.

[Grover, 1997] Grover, L.K. (1997). Quantum Mechanics Helps in Searching for a Needle in a Haystack. *Physical Review Letters*, **79**, 325–8.

[Grover, 1998] Grover, L.K. (1998). Quantum Computers Can Search Rapidly by Using Almost Any Transformation. *Physical Review Letters*, **80**, 4329–32.

[Gruetter *et al*., 1995] Gruetter, P., Mamin, H.J., & Rugar, D. (1995). Magnetic Force Microscopy (MFM). Pages 151–207 of: *Scanning Tunneling Microscopy II*. Berlin: Springer-Verlag.

[Gundlach *et al*., 1996] Gundlach, J.H., Adelberger, E.G., Heckel, B.R., & Swanson, H.E. (1996). New Technique for Measuring Newton's Constant G. *Physical Review D*, **54**, 1256.

[Hagen, 1996] Hagen, Jon B. (1996). *Radio-Frequency Electronics: Circuits and Applications*. Cambridge: Cambridge University Press.

[Hammar *et al*., 1999] Hammar, P.R., Bennett, B.R., Yang, M.J., & Johnson, Mark. (1999). Observation of Spin Injection at a Ferromagnet-Semiconductor Interface. *Physical Review Letters*, **83**, 203–206.

[Hardy & Wright, 1998] Hardy, G.H., & Wright, E.M. (1998). *An Introduction to the Theory of Numbers*. 5th edn. New York: Oxford University Press.

[Hastings *et al*., 1994] Hastings, M.B., Stone, A.D., & Baranger, H.U. (1994). Inequivalence of Weak Localization and Coherent Backscattering. *Physical Review B*, **50**, 8230–44.

[Hawking, 1993] Hawking, S.W. (1993). *Hawking on the Big Bang and Black Holes*. Singapore: World Scientific.

[Heald & Marion, 1995] Heald, Mark A., & Marion, Jerry B. (1995). *Classical Electromagnetic Radiation*. 3rd edn. Fort Worth: Saunders.

[Heath *et al*., 1998] Heath, J.R., Kuekes, P.J., Snider, G.S., & Williams, R.S. (1998). A Defect-Tolerant Computer Architecture: Opportunities for Nanotechnology. *Science*, **280**, 1716–21.

[Herring, 1999] Herring, T.A. (1999). Geodetic Applications of GPS. *Proceedings of the IEEE*, **87**, 92–110.

[Herzig & Dandliker, 1987] Herzig, H.P., & Dandliker, R. (1987). Holographic Optical Scanning Elements: Analytical Method for Determining the Phase Function. *Journal of the Optical Society of America A*, **4**, 1063–70.

[Hill & Peterson, 1993] Hill, Fredrick J., & Peterson, Gerald R. (1993). *Computer Aided Logical Design with Emphasis on VLSI*. 4th edn. New York: Wiley.

[Hoffmann, 1988] Hoffmann, Roald. (1988). *Solids and Surfaces: A Chemist's View of Bonding in Extended Structures*. New York: VCH Publishers.

[Hollister, 1987] Hollister, D.D. (1987). Overview of Advances in Light Sources. *Proceedings of SPIE*, **692**, 170–7.

[Hornbeck, 1998] Hornbeck, Larry J. (1998). From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology. *Texas Instruments Technical Journal*, **15**.

[Horowitz & Hill, 1993] Horowitz, Paul, & Hill, Winfield. (1993). *The Art of Electronics*. 2nd edn. Cambridge: Cambridge University Press.

[Huang *et al*., 1991] Huang, D., Swanson, E.A., Lin, C.P., Schuman, J.S., Stinson, W.G., Chang, W., Hee, M.R., Flotte, T., Gregory, K., Puliafito, C.A., & Fujimoto, J.G. (1991). Optical Coherence Tomography. *Science*, **254**, 1178–81.

[Hughes *et al*., 2000] Hughes, R.J., Buttler, W.T., Kwiat, P.G., Lamoreaux, S.K., Morgan, G.L., Nordholt, J.E., & Peterson, C.G. (2000). Free-Space Quantum Key Distribution in Daylight. *Journal of Modern Optics*, **47**, 549–62.

[Hummel, 1993] Hummel, Rolf E. (1993). *Electronic Properties of Materials*. 2nd edn. Berlin: Springer-Verlag.

[Hunt & Fisher, 1990] Hunt, G.R., & Fisher, W.G. (1990). EMP Ship Trial, Planning, Execution and Result. Pages 308–17 of: *Seventh International Conference on Electromagnetic Compatibility*. IEE, London.

[Jackman *et al*., 1998] Jackman, R.J., Brittain, S.T., Adams, A., Prentiss, M.G., & Whitesides, G.M. (1998). Design and Fabrication of Topologically Complex, Three-Dimensional Microstructures. *Science*, **280**, 2089–91.

[Jackson, 1999] Jackson, John David. (1999). *Classical Electrodynamics*. 3rd edn. New York: Wiley.

[Jedema *et al*., 2001] Jedema, F.J., Filip, A.T., & van Wees, B.J. (2001). Electrical Spin Injection and Accumulation at Room Temperature in an All-Metal Mesoscopic Spin Valve. *Nature*, **410**, 345–348.

[Joannopoulos *et al*., 1997] Joannopoulos, J.D., Villeneuve, P.R., & Fan, S. (1997). Photonic Crystals: Putting a New Twist on Light. *Nature*, **386**, 143–149.

[Johnson & Rahmat-Samii, 1997] Johnson, J.M., & Rahmat-Samii, V. (1997). Genetic Algorithms in Engineering Electromagnetics. *IEEE Antennas & Propagation Magazine*, **39**, 7–21.

[Johnson & Silsbee, 1985] Johnson, Mark, & Silsbee, R. H. (1985). Interfacial Charge-Spin Coupling: Injection and Detection of Spin Magnetization in Metals. *Phys. Rev. Lett*., **55**, 1790–1793.

[Johnson & Jajodia, 1998] Johnson, N.F., & Jajodia, S. (1998). Steganography: Seeing the Unseen. *IEEE Computer*, **31**, 26–34.

[Jones & Mosca, 1998] Jones, J.A., & Mosca, M. (1998). Implementation of a Quantum Algorithm on a Nuclear Magnetic Resonance Quantum Computer. *Journal of Chemical Physics*, **109**, 1648–53.

[Josephson, 1962] Josephson, B.D. (1962). Possible New Effects in Superconductive Tunnelling. *Physics Letters*, **1**, 251.

[Jozsa & Schumacher, 1994] Jozsa, R., & Schumacher, B. (1994). A New Proof of the Quantum Noiseless Coding Theorem. *Journal of Modern Optics*, **41**, 2343–9.

[Jungman *et al*., 1996] Jungman, G., Kamionkowski, M., Kosowsky, A., & Spergel, D.N. (1996). Weighing the Universe with the Cosmic Microwave Background. *Physical Review Letters*, **76**, 1007–10.

[Kak & Slaney, 1988] Kak, A.C., & Slaney, M. (1988). *Principles of Computerized Tomographic Imaging*. New York: IEEE Press.

[Kane, 1998] Kane, B.E. (1998). A Silicon-Based Nuclear Spin Quantum Computer. *Nature*, **393**, 133–7.

[Kastner, 1992] Kastner, M.A. (1992). The Single-Electron Transistor. *Reviews of Modern Physics*, **64**, 849–858.

[Kawai, 1969] Kawai, H. (1969). The Piezoelectricity of Poly(vinylidene Fluoride). *Japanese Journal of Applied Physics*, **8**, 975–6.

[Keller *et al*., 1999] Keller, Mark W., Eichenberger, Ali L., Martinis, John M., & Zimmerman, Neil M. (1999). A Capacitance Standard Based on Counting Electrons. *Science*, **285**, 1706–9.

[Keyes, 1987] Keyes, R.W. (1987). *The Physics of VLSI Systems*. Reading: Addison-Wesley.

[Kino, 1987] Kino, Gordon S. (1987). *Acoustic Waves: Devices, Imaging, and Analog Signal Processing*. Englewood Cliffs: Prentice-Hall.

[Knill *et al.*, 1998a] Knill, E., I., & Laflamme, R. (1998a). Effective Pure States for Bulk Quantum Computation. *Physical Review A*, **57**, 3348–63.
[Knill *et al.*, 1998b] Knill, E., Laflamme, R., & Zurek, W.H. (1998b). Resilient Quantum Computation. *Science*, **279**, 342–5.
[Koblitz, 1994] Koblitz, N. (1994). *A Course in Number Theory and Cryptography*. New York: Springer-Verlag.
[Koenen, 1999] Koenen, R. (1999). MPEG-4: Multimedia For Our Time. *IEEE Spectrum*, **36**, 26–33.
[Kusch, 1949] Kusch, P. (1949). Some Design Considerations of an Atomic Clock using Atomic Beam Techniques. *Physical Review*, **76**, 161.
[Kwong, 1995] Kwong, K.K. (1995). Functional Magnetic Resonance Imaging with Echo Planar Imaging. *Magnetic Resonance Quarterly*, **11**, 1–20.
[Land, 1951] Land, E.H. (1951). Some Aspects of the Development of Sheet Polarizers. *Journal of the Optical Society of America*, **41**, 956–63.
[Landauer, 1961] Landauer, Rolf. (1961). Irreversibility and Heat Generation in the Computing Process. *IBM Journal of Research and Development*, **5**, 183–91.
[Landman & Russo, 1971] Landman, E.S., & Russo, R.L. (1971). On a Pin Versus Block Relationships for Partitions of Logic Graphs. *IEEE Transactions on Computers*, **C20**, 1469–79.
[Larsen, 1973] Larsen, K.J. (1973). Short Convolutional Codes with Maximal Free Distance for Rates 1/2, 1/3, and 1/4. *IEEE Transactions on Information Theory*, **IT-19**, 371–2.
[Lauterbur, 1973] Lauterbur, P.C. (1973). Image Formation by Induced Local Interactions: Examples Employing Nuclear Magnetic Resonance. *Nature*, **242**, 190–1.
[Leff & Rex, 1990] Leff, Harvey S. & Rex, Andrew F. (eds). (1990). *Maxwell's Demon: Entropy, Information, Computing*. Princeton: Princeton University Press.
[Lehrman & Tully, 1993] Lehrman, Paul D., & Tully, Tim. (1993). *MIDI For The Professional*. New York: Amsco Publications.
[Lenstra & Lenstra, Jr., 1993] Lenstra, A.K., & Lenstra, Jr., H.W. (eds). (1993). *The Development of the Number Field Sieve*. Lecture Notes in Math, 1554. New York: Springer-Verlag.
[Leonhardt & Tyc, 2009] Leonhardt, Ulf, & Tyc, Tomáš. (2009). Broadband Invisibility by Non-Euclidean Cloaking. *Science*, **323**, 110–112.
[Lerner & Trigg, 2005] Lerner, Rita G., & Trigg, George L. (eds). (2005). *Encyclopedia of Physics*. 3rd edn. New York: Wiley.
[Lichtman, 1994] Lichtman, J.W. (1994). Confocal Microscopy. *Scientific American*, **271**, 30–5.
[Likharev, 1999] Likharev, K. (1999). Superconductor Devices for Ultrafast Computing. Weinstock, H. (ed), *Applications of Superconductivity*. Dordrecht: Kluwer.
[Likharev & Claeson, 1992] Likharev, K.K., & Claeson, T. (1992). Single Electronics. *Scientific American*, **266**, 50–5.
[Lin *et al.*, 2009] Lin, Yu-Ming, andAlberto Valdes-Garcia, Keith A. Jenkins, Small, Joshua P., Farmer, Damon B., & Avouris, Phaedon. (2009). Operation of Graphene Transistors at Gigahertz Frequencies. *Nano Letters*, **9**, 422–426.
[Lind & Marcus, 1995] Lind, Douglas, & Marcus, Brian. (1995). *An Introduction to Symbolic Dynamics and Coding*. Cambridge: Cambridge University Press.
[Linden *et al.*, 1999] Linden, N., Barjat, H., Kupce, E., & Freeman, R. (1999). How to Exchange Information Between Two Coupled Nuclear Spins: the Universal SWAP Operation. *Chemical Physics Letters*, **307**, 198–204.
[Liu *et al.*, 2001] Liu, C., Dutton, Z., Behroozi, C.H., & Hau, L.V. (2001). Observation of Coherent Optical Information Storage in an Atomic Medium using Halted Light Pulses. *Nature*, **409**, 490–493.
[Lloyd, 1993] Lloyd, S. (1993). A Potentially Realizable Quantum Computer. *Science*, **261**, 1569–71.

[Lloyd, 1996] Lloyd, S. (1996). Universal Quantum Simulators. *Science*, **273**, 1073–8.
[Lloyd, 1997] Lloyd, S. (1997). Capacity of the Noisy Quantum Channel. *Physical Review A*, **55**, 1613–22.
[Lloyd, 2000] Lloyd, S. (2000). Ultimate Physical Limits to Computation. *Nature*, **406**, 1047–1054.
[Lo & Chau, 1999] Lo, H.K., & Chau, H.F. (1999). Unconditional Security of Quantum Key Distribution over Arbitrarily Long Distances. *Science*, **283**, 2050–6.
[Lott *et al*., 1993] Lott, J.A., Schneider, R.P., Choquette, K.D., Kilcoyne, S.P., & Figiel, J.J. (1993). Room Temperature Continuous Wave Operation of Red Vertical Cavity Surface Emitting Laser Diodes. *Electronics Letters*, **29**, 1693–4.
[Lucente, 1997] Lucente, Mark. (1997). Interactive Three-Dimensional Holographic Displays: Seeing the Future in Depth. *Computer Graphics*, **31**, 63–7.
[Luo *et al*., 2002] Luo, C., Johnson, S.G., Joannopoulos, J.D., & Pendry, J.B. (2002). All-Angle Negative Refraction Without Negative Effective Index. *Physical Review B*, **65**, 201104.
[Major, 1998] Major, Fouad G. (1998). *The Quantum Beat: The Physical Principles of Atomic Clocks*. New York: Springer.
[Mallinson, 1993] Mallinson, J.C. (1993). *The Foundations of Magnetic Recording*. 2nd edn. Boston: Academic Press.
[Mallinson, 1996] Mallinson, J.C. (1996). Scaling in Magnetic Recording. *IEEE Transactions on Magnetics*, **32**, 599–600.
[Mandelbrot, 1983] Mandelbrot, Benoit B. (1983). *The Fractal Geometry of Nature*. New York: W.H. Freeman.
[Marqués *et al*., 2003] Marqués, R., Mesa, F., Martel, J., & Medina, F. (2003). Comparative Analysis of Edge- and Broadside-Coupled Split Ring Resonators for Metamaterial Design–Theory and Experiments. *IEEE Transactions on Antennas and Propagation*, **51**, 2572–2581.
[Mattis, 1988] Mattis, Daniel C. (1988). *The Theory of Magnetism I: Statics and Dynamics*. New York: Springer-Verlag.
[Maxwell, 1998] Maxwell, James Clerk. (1998). *A Treatise on Electricity and Magnetism*. 3rd edn. Oxford: Oxford University Press. First published in 1873.
[McCluskey, 1956] McCluskey, E.J. (1956). Minimization of Boolean Functions. *Bell System Technical Journal*, **35**, 1417–44.
[McKittrick *et al*., 1999] McKittrick, J., Kassner, M.E., & Shea, L.E. (1999). Materials Issues in Flat Panel Displays: Phosphor Selection and Optimization. *Proceedings of SPIE*, **3582**, 565–70.
[Mee & Daniel, 1996] Mee, C. Denis, & Daniel, Eric D. (eds). (1996). *Magnetic Storage Handbook*. 2nd edn. New York: McGraw-Hill.
[Merkle, 1978] Merkle, R. (1978). Secure Communications over Insecure Channels. *Communications of the ACM*, **21**, 294–9.
[Merkle, 1993] Merkle, R.C. (1993). Reversible electronic logic using switches. *Nanotechnology*, **4**, 21–40.
[Merkle, 1998] Merkle, R.C. (1998). Making Smaller, Faster, Cheaper Computers. *Proceedings of the IEEE*, **86**, 2384–6.
[Mermin, 1985] Mermin, N.D. (1985). Is the moon there when nobody looks? Reality and the quantum theory. *Physics Today*, **38**, 38–47.
[Mermin, 1993] Mermin, N.D. (1993). Hidden Variables and the Two Theorems of John Bell. *Reviews of Modern Physics*, **65**, 803–15.
[Merzbacher *et al*., 1996] Merzbacher, C.I., Kersey, A.D., & Friebele, E.J. (1996). Fiber Optic Sensors in Concrete Structures: A Review. *Smart Materials & Structures*, **5**, 196–208.
[Millman & Grabel, 1987] Millman, Jacob, & Grabel, Arvin. (1987). *Microelectronics*. 2nd edn. New York: McGraw-Hill.
[Minsky, 1957] Minsky, Marvin. (1957). *Microscopy Apparatus*. US Patent No. 3 013 467.

[Misner *et al.*, 1973] Misner, C.W., Wheeler, J.A., & Thorne, K.S. (1973). *Gravitation*. New York: W.H. Freeman & Co.

[Mitchell & George, 1998] Mitchell, S., & George, R. (1998). EMP Protection. *Electrotechnology*, **9**, 33–5.

[Miya *et al.*, 1979] Miya, T., Terunuma, Y., Hosaka, T., & Miyashita, T. (1979). Ultimate Low-Loss Single-Mode Fibre at 1.55 $\mu$m. *Electronics Letters*, **15**, 106–8.

[Mohr *et al.*, 2008] Mohr, Peter J., Taylor, Barry N., & Newell, David B. (2008). CODATA Recommended Values of the Fundamental Physical Constants: 2006. *Rev. Mod. Phys.*, **80**(2), 633–730.

[Mollenauer *et al.*, 1996] Mollenauer, L.F., Mamyshev, P.V., & Neubelt, M.J. (1996). Demonstration of Soliton WDM Transmission at 6 and 7*10 Gbit/s, Error Free Over Transoceanic Distances. *Electronics Letters*, **32**, 471–3.

[Montroll & Lebowitz, 1987] Montroll, E.W., & Lebowitz, J.L. (eds). (1987). *Fluctuation Phenomena*. New York: North-Holland.

[Mooij *et al.*, 1999] Mooij, J.E., Orlando, T.P., Levitov, L., Tian, L., van der Wal, C.H., & Lloyd, S. (1999). Josephson Persistent-Current Qubit. *Science*, **285**, 1036–9.

[Moore, 1979] Moore, G. (1979). VLSI: Some Fundamental Challenges. *IEEE Spectrum*, **16**, 30.

[Morrison & Morrison, 1982] Morrison, Philip, & Morrison, Phylis. (1982). *Powers Of Ten: A Book About the Relative Size of Things*. Redding: Scientific American Library.

[Mukai *et al.*, 1999] Mukai, T., Yamada, M., & Nakamura, S. (1999). Characteristic of InGaN-based UV/Blue/Green/Amber/Red Light-Emitting Diodes. *Japanese Journal of Applied Physics*, **38**, 3976–81.

[Muller *et al.*, 1996] Muller, A., Zbinden, H., & Gisin, N. (1996). Quantum Cryptography over 23 km in Installed Under-Lake Telecom Fibre. *Europhysics Letters*, **33**, 335–9.

[Nachtmann, 1990] Nachtmann, Otto. (1990). *Elementary Particle Physics: Concepts and Phenomena*. New York: Springer-Verlag. Translated by A. Lahee and W. Wetzel.

[Nakamura *et al.*, 2000] Nakamura, Shuji, Senoh, Masayuki, ichi Nagahama, Shin, Iwasa, Naruhito, Matsushita, Toshio, & Mukai, Takashi. (2000). Blue InGaN-Based Laser Diodes with an Emission Wavelength of 450 nm. *Applied Physics Letters*, **76**, 22–24.

[Nakashima, 1998] Nakashima, H. (1998). Present Status of Progress in MAGLEV Development. *Japanese Railway Engineering*, **37**, 6–8.

[Nakazawa *et al.*, 1993] Nakazawa, M., Kimura, Y., & Suzuki, K. (1993). Nonlinear Optics in Optical Fibers and Future Prospects for Optical Soliton Communications Technologies. *NTT R&D*, **42**, 1317–26.

[Nielsen & Chuang, 2000] Nielsen, M.A., & Chuang, I.L. (2000). *Quantum Computation and Quantum Information*. Cambridge: Cambridge University Press.

[Ogawa *et al.*, 1990] Ogawa, S., Lee, T.M., Kay, A.R., & Tank, D.W. (1990). Brain Magnetic Resonance Imaging with Contrast Dependent on Blood Oxygenation. *Proceedings of the National Academy of Sciences*, **87**, 9868–72.

[O'Handley, 1999] O'Handley, Robert C. (1999). *Modern Magnetic Materials: Principles and Applications*. Hoboken, NJ: Wiley-Interscience.

[O'Mara, 1993] O'Mara, William C. (1993). *Liquid Crystal Flat Panel Displays: Manufacturing Science & Technology*. New York: Van Nostrand Reinhold.

[Ono & Yano, 1998] Ono, T., & Yano, Y. (1998). Key Technologies for Terabit/Second WDM Systems with High Spectral Efficiency of over 1 bit/s/Hz. *IEEE Journal of Quantum Electronics*, **34**, 2080–8.

[Onsager, 1931] Onsager, L. (1931). *Physical Review*, **38**, 2265.

[Pai & Springett, 1993] Pai, D.M., & Springett, B.E. (1993). Physics of Electrophotography. *Reviews of Modern Physics*, **65**, 163–211.

[Pappu *et al*., 2002] Pappu, Ravikanth, Recht, Ben, Taylor, Jason, & Gershenfeld, Neil. (2002). Physical One-Way Functions. *Science*, **297**, 2026–2030.
[Parkin, 1994] Parkin, S.S.P. (1994). Materials Update: Giant Magnetoresistance in Magnetic Multilayers and Granular Alloys. *Materials Letters*, **20**, 1–4.
[Pavlidis, 1999] Pavlidis, D. (1999). HBT vs. PHEMT vs. MESFET: What's Best and Why. *Compound Semiconductor*, **5**, 56–9.
[Pendry, 2000] Pendry, J.B. (2000). Negative Refraction Makes a Perfect Lens. *Physical Review Letters*, **85**, 3966–3969.
[Pendry *et al*., 1998] Pendry, J.B., Holden, A.J., Robbins, D.J., & Stewart, W.J. (1998). Low Frequency Plasmons in Thin-Wire Structures. *J. Phys. Condens. Matter*, **10**, 4785–4809.
[Pendry *et al*., 1999] Pendry, J.B., Holden, A.J., Robbins, D.J., & Stewart, W.J. (1999). Magnetism from Conductors and Enhanced Nonlinear Phenomena. *IEEE Transactions of Microwave Theory and Techniques*, **47**, 2075–2084.
[Pendry *et al*., 2006] Pendry, J.B., Schurig, D., & Smith, D.R. (2006). Controlling Electromagnetic Fields. *Science*, **312**, 1780–1782.
[Peres, 1990] Peres, A. (1990). Incompatible Results of Quantum Measurements. *Physics Letters A*, **151**, 107–8.
[Peres, 1993] Peres, Asher. (1993). *Quantum Theory: Concepts and Methods*. Boston: Kluwer Academic.
[Peters *et al*., 1999] Peters, A., Chung, K.Y., & Chu, S. (1999). Measurement of Gravitational Acceleration by Dropping Atoms. *Nature*, **400**, 849–52.
[Phillips *et al*., 2001] Phillips, D.F., Fleischhauer, A., Mair, A., Walsworth, R.L., & Lukin, M.D. (2001). Storage of Light in Atomic Vapor. *Physical Review Letters*, **86**, 783–786.
[Phillips *et al*., 1998] Phillips, P.M., Spindt, C.A., Holland, C.E., Schwoebel, P.R., & Brodie, I. (1998). Development of Spindt Cathodes for High Frequency Devices and Flat Panel Display Applications. *Proceedings of SPIE*, **3465**, 90–7.
[Posner & Stevens, 1984] Posner, E.C., & Stevens, R. (1984). Deep Space Communication – Past, Present, and Future. *IEEE Communications Magazine*, **22**, 8–21.
[Postma *et al*., 2001] Postma, Henk W. Ch., Teepen, Tijs, Yao, Zhen, Grifoni, Milena, & Dekker, Cees. (2001). Carbon Nanotube Single-Electron Transistors at Room Temperature. *Science*, **293**, 76–79.
[Press *et al*., 2007] Press, William H., Teukolsky, Saul A., Vetterling, William T., & Flannery, Brian P. (2007). *Numerical Recipes in C: The Art of Scientific Computing*. 3nd edn. Cambridge: Cambridge University Press.
[Pritchard & Gibson, 1980] Pritchard, D., & Gibson, J. (1980). Worldwide Color Television Standards. *J. Soc. Motion. Pict. Telev. Eng*., **89**, 111–120.
[Quine, 1952] Quine, W.V. (1952). The Problem of Simplifying Truth Functions. *American Mathematical Monthly*, **59**, 521–31.
[Radon, 1917] Radon, J. (1917). On The Determination Of Functions From Their Integrals Along Certain Manifolds. *Berichte Saechsische Akademie der Wissenschaften*, **29**, 262–77.
[Rallison, 1984] Rallison, R. (1984). Applications of Holographic Optical Elements. *Lasers & Applications*, **3**, 61–8.
[Ramirez, 1997] Ramirez, A.P. (1997). Colossal Magnetoresistance. *J. Phys.: Condens. Matter*, **9**, 8171–8199.
[Ramirez *et al*., 1997] Ramirez, A.P., Cheong, S-W, & Schiffer, P. (1997). Colossal Magnetoresistance and Charge Order in $La_{1-x}Ca_xMnO_3$. *Journal of Applied Physics*, **81**, 5337–42.
[Ramo *et al*., 1994] Ramo, Simon, Whinnery, John R., & Duzer, Theodore Van. (1994). *Fields and Waves in Communication Electronics*. 3rd edn. New York: Wiley.
[Ramsey, 1980] Ramsey, N.F. (1980). The Method of Successive Oscillatory Fields. *Physics Today*, **33**, 25–30.

[Rauf & Kushner, 1999] Rauf, S., & Kushner, M.J. (1999). Dynamics of a Coplanar-Electrode Plasma Display Panel Cell. I. Basic Operation. *Journal of Applied Physics*, **85**, 3460–9.

[Reichl, 1998] Reichl, L.E. (1998). *A Modern Course in Statistical Physics*. 2nd edn. New York: Wiley.

[Reif, 1965] Reif, F. (1965). *Fundamentals of Statistical and Thermal Physics*. New York: McGraw-Hill.

[Ridley *et al*., 1999] Ridley, B., Nivi, B., & Jacobson, J. (1999). All-Inorganic Field Effect Transistors Fabricated by Printing. *Science*, **286**, 746–9.

[Rivest *et al*., 1978] Rivest, R.L., Shamir, A., & Adleman, L.M. (1978). A Method of Obtaining Digital Signatures and Public-Key Cryptosystems. *Communications of the ACM*, **21**, 120–6.

[Rodgers *et al*., 1997] Rodgers, M.S., Sniegowski, J.J., Miller, S.L., Barron, C., & PJ, P.J. McWhorter. (1997). Advanced Micromechanisms in a Multi-Level Polysilicon Technology. *Proceedings of SPIE*, **3224**, 120–30.

[Rogers & Buhrman, 1984] Rogers, C.T., & Buhrman, R.A. (1984). Composition of $1/f$ Noise in Metal–Insulator–Metal Tunnel Junctions. *Physical Review Letters*, **53**, 1272–5.

[Rogers & Nuzzo, 2005] Rogers, John A., & Nuzzo, Ralph G. (2005). Recent Progress in Soft Lithography. *Materials Today*, 50–56.

[Rüeger, 1990] Rüeger, J.M. (1990). *Electronic Distance Measurement*. 3rd edn. New York: Springer-Verlag.

[Sakurai, 1967] Sakurai, J.J. (1967). *Advanced Quantum Mechanics*. Reading: Addison-Wesley.

[Schack & Caves, 1999] Schack, R., & Caves, C.M. (1999). Classical Model for Bulk-Ensemble NMR Quantum Computation. *Physical Review A*, **60**, 4354–62.

[Schadt & Helfrich, 1971] Schadt, M., & Helfrich, W. (1971). Voltage-Dependent Optical Activity of a Twisted Nematic Liquid Crystal. *Applied Physics Letters*, **18**, 127–8.

[Schroeder, 1990] Schroeder, M.R. (1990). *Number Theory in Science and Communication*. 2nd edn. New York: Springer-Verlag.

[Schroeder *et al*., 1979] Schroeder, M.R., Atal, B.S., & Hall, J.L. (1979). Optimizing digital speech coders by exploiting masking properties of the human ear. *Journal of the Acoustical Society of America*, **66**, 1647–52.

[Schwarze *et al*., 1993] Schwarze, V.S., Hartmann, T., Leins, M., & Soffel, M.H. (1993). Relativistic Effects in Satellite Positioning. *Manuscripta Geodaetica*, **18**, 306–16.

[Scott, 1998] Scott, J.F. (1998). Status Report on Ferroelectric Memory Materials. *Integrated Ferroelectrics*, **20**, 15–23.

[Sheats *et al*., 1996] Sheats, J.R., Antoniadis, H., Hueschen, M., Leonard, W., Miller, J., Moon, R., Roitman, D., & Stocking, A. (1996). Organic Electroluminescent Devices. *Science*, **273**, 884–8.

[Shepherd, 1990] Shepherd, G. (1990). *The Synaptic Organization of the Brain*. 3rd edn. New York: Oxford University Press.

[Shor, 1995] Shor, P.W. (1995). Scheme for Reducing Decoherence in Quantum Computer Memory. *Physical Review A*, **52**, 2493–6.

[Shor, 1996] Shor, P.W. (1996). Fault-Tolerant Quantum Computation. Pages 56–65 of: *Proceedings of the 37th Annual Symposium Foundations of Computer Science*. Los Alamitos: IEEE Computer Society Press.

[Shor, 1997] Shor, P.W. (1997). Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer. *SIAM Journal on Computing*, **26**, 1484–509.

[Shung *et al.*, 1992] Shung, K. Kirk, Smith, Michael B., & Tsui, Benjamin. (1992). *Principles of Medical Imaging*. San Diego: Academic Press.

[Sikora, 1997] Sikora, T. (1997). MPEG Digital Video-Coding Standards. *IEEE Signal Processing Magazine*, **14**, 82–100.

[Simmons, 1992] Simmons, G.J. (ed). (1992). *Contemporary Cryptology: The Science of Information Integrity*. Piscataway: IEEE Press.

[Simon *et al.*, 1994] Simon, M.K., Omura, J.K., Scholtz, R.A., & Levitt, B.K. (1994). *Spread Spectrum Communications Handbook*. New York: McGraw-Hill.

[Sklar, 1988] Sklar, Bernard. (1988). *Digital Communications: Fundamentals and Applications*. Englewood Cliffs: Prentice Hall.

[Skolnik, 1990] Skolnik, Merrill I. (ed). (1990). *Radar Handbook*. 2nd edn. New York: McGraw-Hill.

[Slepian, 1974] Slepian, David (ed). (1974). *Key Papers in the Development of Information Theory*. New York: IEEE Press.

[Slichter, 1992] Slichter, Charles P. (1992). *Principles of Magnetic Resonance*. 3rd edn. New York: Springer-Verlag.

[Smith *et al.*, 2004] Smith, D.R., Pendry, J.B., & Wiltshire, M.C.K. (2004). Metamaterials and Negative Refractive Index. *Science*, **305**, 788–792.

[Smith, 1996] Smith, J.R. (1996). Field Mice: Extracting Hand Geometry From Electric Field Measurements. *IBM Systems Journal*, **35**, 587–608.

[Smith, 1999] Smith, J.R. (1999). *Electric Field Imaging*. Ph.D. thesis, MIT.

[Snider & Williams, 2007] Snider, Gregory S., & Williams, R. Stanley. (2007). Nano/CMOS Architectures Using a Field-Programmable Nanowire Interconnect. *Nanotechnology*, **18**, 1–11.

[Sobel, 1996] Sobel, Dava. (1996). *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*. New York: McGraw-Hill.

[Somaroo *et al.*, 1999] Somaroo, S., Tseng, C.H., Havel, T.F, Laflamme, R., & Cory, D.G. (1999). Quantum Simulations on a Quantum Computer. *Physical Review Letters*, **82**, 5381–4.

[Someya *et al.*, 1999] Someya, T., Werner, R., Forchel, A., Catalano, M., Cingolani, R., & Arakawa, Y. (1999). Room Temperature Lasing at Blue Wavelengths in Gallium Nitride Microcavities. *Science*, **285**, 1905–6.

[Song *et al.*, 1999] Song, Y.Q., Goodson, B.M., & Pines, A. (1999). NMR and MRI using Laser-Polarized Xenon. *Spectroscopy*, **14**, 26–33.

[Sourlas, 1989] Sourlas, N. (1989). Spin-Glass Models as Error-Correcting Codes. *Nature*, **339**, 693–5.

[Spuhler, 1983] Spuhler, H. (1983). Where Fluidics Still Makes Sense. *Machine Design*, **55**, 92–4.

[Starkweather, 1980] Starkweather, G.K. (1980). High-Speed Laser Printing Systems. Pages 125–89 of: *Laser Applications*, vol. 4. New York: Academic Press.

[Steane, 1996] Steane, A.M. (1996). Error Correcting Codes in Quantum Theory. *Physical Review Letters*, **77**, 793–7.

[Stehling *et al.*, 1991] Stehling, M.K., Turner, R., & Mansfield, P. (1991). Echo-planar Imaging: Magnetic Resonance Imaging In A Fraction Of A Second. *Science*, **254**, 43–50.

[Stern, 1996] Stern, M.B. (1996). Binary Optics: a VLSI-based microoptics Technology. *Microelectronic Engineering*, **32**, 369–88.

[Stofan *et al.*, 1995] Stofan, E.R., Evans, D.L., Schmullius, C., Holt, B., Plaut, J.J., van Zyl, J., Wall, S.D., & Way, J. (1995). Overview of Results of Spaceborne Imaging Radar-C, X-Band Synthetic Aperture Radar (SIR-C/X-SAR). *IEEE Transactions on Geoscience & Remote Sensing*, **33**, 817–28.

[Strang, 1988] Strang, Gilbert. (1988). *Linear Algebra and its Applications*. 3rd edn. San Diego: Harcourt, Brace, Jovanovich.

[Streetman & Banerjee, 2005] Streetman, Ben, & Banerjee, Sanjay. (2005). *Solid State Electronic Devices*. 6th edn. Englewood Cliffs: Prentice-Hall.

[Stroscio & Eigler, 1991] Stroscio, J.A., & Eigler, D.M. (1991). Atomic and Molecular Manipulation with the Scanning Tunneling Microscope. *Science*, **254**, 319–26.

[Strukov & Likharev, 2005] Strukov, Dmitri B, & Likharev, Konstantin K. (2005). CMOL FPGA: a Reconfigurable Architecture for Hybrid Digital Circuits With Two-Terminal Nanodevices. *Nanotechnology*, **16**, 888–900.

[Strukov *et al*., 2008] Strukov, Dmitri B., Snider, Gregory S., Stewart, Duncan R., & Williams, R. Stanley. (2008). The Missing Memristor Found. *Nature*, **453**, 80–83.

[Sun & Rogers, 2007] Sun, Yugang, & Rogers, John A. (2007). Inorganic Semiconductors for Flexible Electronics. *Adv. Mater.*, **19**, 1897–1916.

[Surguy, 1993] Surguy, P.W.H. (1993). The Development of Ferroelectric LCDs for Display Applications. *Journal of the Society for Information Display*, **1**, 247–54.

[Sweatt, 1979] Sweatt, W.C. (1979). Mathematical Equivalence Between a Holographic Optical Element and an Ultra-High Index Lens. *Journal of the Optical Society of America*, **69**, 486–7.

[Sze, 1981] Sze, S.M. (1981). *Physics of Semiconductor Devices*. 2nd edn. New York: Wiley-Interscience.

[Sze, 1998] Sze, S.M. (ed). (1998). *Modern Semiconductor Device Physics*. New York: Wiley-Interscience.

[Takahashi, 1993] Takahashi, S. (1993). Fibers for Optical Communications. *Advanced Materials*, **5**, 187–91.

[Takashi M. Ukai & Nakamura, 1999] Takashi M. Ukai, Motokazu Yamada, & Nakamura, Shuji. (1999). Characteristics of InGaN-Based UV/Blue/Green/Amber/Red Light-Emitting Diodes. *Jpn. J. Appl. Phys.*, **38**, 3976–3981.

[Tans *et al*., 1998] Tans, Sander J., Verschueren, Alwin R.M., & Dekker, Cees. (1998). Room-Temperature Transistor Based on a Single Carbon Nanotube. *Nature*, **393**, 49–52.

[Taylor & Wheeler, 1992] Taylor, Edwin F., & Wheeler, John Archibald. (1992). *Spacetime Physics: Introduction to Special Relativity*. 2nd edn. New York: W.H. Freeman.

[Tehrani *et al*., 1999] Tehrani, S., Slaughter, J.M., Chen, E., Durlam, M., Shi, J., & DeHerren, M. (1999). Progress and Outlook for MRAM Technology. *IEEE Transactions on Magnetics*, **35**, 2814–2819.

[Thomson, 1857] Thomson, W. (1857). On the Electro-Dynamic Qualities of Metals: Effects of Magnetization on the Electric Conductivity of Nickel and of Iron. *Proc. R. Soc. Lond.*, **8**, 546–550.

[Tinkham, 1995] Tinkham, Michael. (1995). *Introduction to Superconductivity*. 2nd edn. New York: McGraw-Hill.

[Tittel *et al*., 1998] Tittel, W., Brendel, J., Zbinden, H., & Gisin, N. (1998). Violation of Bell Inequalities by Photons More than 10 km Apart. *Physical Review Letters*, **81**, 3563–6.

[Todorovic *et al*., 1999] Todorovic, M., Schultz, S., Wong, J., & Scherer, A. (1999). Writing and Reading of Single Magnetic Domain Per Bit Perpendicular Patterned Media. *Applied Physics Letters*, **74**, 2516–18.

[Tsang & Psaltis, 2008] Tsang, M., & Psaltis, D. (2008). Magnifying Perfect Lens and Superlens Design by Coordinate Transformation. *Physical Review B*, **77**, 035122.

[Turing, 1936] Turing, A.M. (1936). On Computable Numbers, with an Application to the *Entscheidungsproblem*. *Proc. London Math. Soc.*, **42**, 230–65.

[Turing, 1950] Turing, A.M. (1950). Computing Machinery and Intelligence. *Mind*, **59**, 433–560.

[Underkoffler *et al.*, 1999] Underkoffler, J., Ullmer, B., & Ishii, H. (1999). Emancipated Pixels: Real-World Graphics in the Luminous Room. Pages 385–92 of: *Proceedings of SIGGRAPH '99*. New York: ACM Press.
[Unruh, 1995] Unruh, W.G. (1995). Maintaining Coherence in Quantum Computers. *Physical Review A*, **51**, 992–7.
[Žutić *et al.*, 2004] Žutić, Igor, Fabian, Jaroslav, & Sarma, S. Das. (2004). Spintronics: Fundamentals and Applications. *Reviews of Modern Physics*, **76**, 323–410.
[van Kessel *et al.*, 1998] van Kessel, P.F., Hornbeck, L.J., RE, R.E. Meier, & Douglass, M.R. (1998). A MEMS-Based Projection Display. *Proceedings of the IEEE*, **86**, 1687–704.
[Veselago, 1968] Veselago, V.G. (1968). The Electrodynamics of Substances with Simultaneously Negative Values of $\epsilon$ and $\mu$. *Soviet Physics Uspekhi*, **10**, 509–514.
[Vigoda *et al.*, 2006] Vigoda, B., Dauwels, H., Frey, M., Gershenfeld, N., Koch, T., Loeliger, H.-A., & Merkli, P. (2006). Synchronization of Pseudo-Random Signals by Forward-Only Message Passing with Application to Electronics Circuits. *IEEE Transactions of Information Theory*, **52**, 3843–3852.
[Vilkelis, 1982] Vilkelis, W.V. (1982). Lead Reduction among Combinatorial Logic Circuits. *IBM Journal of Research and Development*, **26**, 342–348.
[Viterbi & Omura, 1979] Viterbi, Andrew J., & Omura, Jim K. (1979). *Principles of Digital Communication and Coding*. New York: McGraw-Hill.
[von Neumann, 1956] von Neumann, J. (1956). Probabilistic Logics and the Synthesis of Reliable Organisms from Unreliable Components. Pages 43–98 of: Shannon, C., & McCarthy, J. (eds), *Automata Studies*. Princeton: Princeton University Press.
[Walls & Vig, 1995] Walls, F.L., & Vig, J.R. (1995). Fundamental Limits on the Frequency Stabilities of Crystal Oscillators. *IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control*, **42**, 576–89.
[Wang, 1989] Wang, Shyh. (1989). *Fundamentals of Semiconductor Theory and Device Physics*. Englewood Cliffs: Prentice-Hall.
[Weber *et al.*, 2000] Weber, M.F., Stover, C.A., Gilbert, L.R., Nevitt, T.J., & Ouderkirk, A.J. (2000). Giant Birefringent Optics in Multilayer Polymer Mirrors. *Science*, **287**, 2451–2455.
[Weinacht *et al.*, 1999] Weinacht, T.C., Ahn, J., & Bucksbaum, P.H. (1999). Controlling the Shape of a Quantum Wavefunction. *Nature*, **397**, 233–5.
[Weinberg, 1989] Weinberg, S. (1989). Testing Quantum Mechanics. *Annals of Physics*, **194**, 336–86.
[Welch, 1984] Welch, Terry A. (1984). A Technique for High Performance Data Compression. *IEEE Computer*, **17**, 8–19.
[Wieman *et al.*, 1999] Wieman, C.E., Pritchard, D.E., & Wineland, D.J. (1999). Atom Cooling, Trapping, and Quantum Manipulation. *Reviews of Modern Physics*, **71**, S253–62.
[Wiesner, 1983] Wiesner, S. (1983). Conjugate Coding. *Sigact News*, **15**, 78–88.
[Williams, 1993] Williams, Edgar M. (1993). *The Physics and Technology of Xerographic Processes*. Malabar: Krieger.
[Winograd & Cowan, 1963] Winograd, S., & Cowan, J.D. (1963). *Reliable Computation in the Presence of Noise*. Cambridge: MIT Press.
[Wojtkowski *et al.*, 2004] Wojtkowski, Maciej, Srinivasan, Vivek J., Ko, Tony H., Fujimoto, James G., Kowalczyk, Andrzej, & Duker, Jay S. (2004). Ultrahigh-Resolution, High-Speed, Fourier Domain Optical Coherence Tomography and Methods for Dispersion Compensation. *Optics Express*, **12**, 2404–2422.
[Wolaver, 1991] Wolaver, Dan H. (1991). *Phase-Locked Loop Circuit Design*. Englewood Cliffs: Prentice Hall.

[Wolf *et al*., 2001] Wolf, S.A., Awschalom, D.D., Buhrman, R.A., Daughton, J.M., von Molnar, S., Roukes, M.L., Chtchelkanova, A.Y., & Treger, D.M. (2001). Spintronics: A Spin-Based Electronics Vision for the Future. *Science*, **294**, 1488–1495.

[Wooters & Zurek, 1982] Wooters, W.K., & Zurek, W.H. (1982). A Single Quantum Cannot Be Cloned. *Nature*, **299**, 802–3.

[Wright, 1998] Wright, H. (1998). Observe Digital Modualtion Through Diagrams. *Test and Measurement World*, 61–64.

[Xia & Whitesides, 1998] Xia, Younan, & Whitesides, George M. (1998). Soft Lithography. *Annu. Rev. Mater. Sci.*, **28**, 153–84.

[Yablonovitch, 1993] Yablonovitch, E. (1993). Photonic Band-Gap Structures. *J. Opt. Soc. Am. B*, **10**, 283–295.

[Yariv, 1987] Yariv, A. (1987). Operator Algebra for Propagation Problems involving Phase Conjugation and Nonreciprocal Elements. *Applied Optics*, **26**, 4538–40.

[Yariv, 1991] Yariv, A. (1991). *Optical Electronics*. 4th edn. Philadelphia: Saunders College Publishing.

[Yariv & Pepper, 1977] Yariv, A., & Pepper, D.M. (1977). Amplified Reflection, Phase Conjugation, and Oscillation in Degenerate Four-Wave Mixing. *Optics Letters*, **1**, 16–18.

[Yariv & Yeh, 2006] Yariv, Amnon, & Yeh, Pochi. (2006). *Photonics: Optical Electronics in Modern Communications*. New York: Oxford University Press.

[Ye *et al*., 1999] Ye, J., Vernooy, D.W., & Kimble, H.J. (1999). Trapping of Single Atoms in Cavity QED. *Physical Review Letters*, **83**, 4987–90.

[Yoo *et al*., 1989] Yoo, K.M., Takiguchi, Y., & Alfano, R.R. (1989). Dynamic Effect of Weak Localization on the Light Scattering from Random Media using Ultrafat Laser Technology. *Applied Optics*, **28**, 2343–9.

[Younis & Knight, 1993] Younis, S., & Knight, T. (1993). Practical Implementation of Charge Recovering Asymptotically Zero Power CMOS. Pages 234–50 of: *Proceeding of the 1993 Symposium on Integrated Systems*. Cambridge: MIT Press.

[Yourgrau *et al*., 1982] Yourgrau, Wolfgang, van der Merwe, Alwyn, & Raw, Gough. (1982). *Treatise on Irreversible and Statistical Thermophysics: An Introduction to Nonclassical Thermodynamics*. New York: Dover.

[Zabusky, 1981] Zabusky, N.J. (1981). Computational Synergetics and Mathematical Innovation. *Journal of Computational Physics*, **43**, 195–249.

[Zhua & Park, 2006] Zhua, Jian-Gang, & Park, Chando. (2006). Magnetic Tunnel Junctions. *Materials Today*, **9**, 36–45.

[Zimmerman, 1998] Zimmerman, NM. (1998). A Primer on Electrical Units in the Systeme International. *American Journal of Physics*, **66**, 324–31.

[Zurek, 1998] Zurek, W.H. (1998). Decoherence, Einselection and the Existential Interpretation (The Rough Guide). *Philosophical Transactions of the Royal Society of London Series A*, **356**, 1793–821.