THE ROAD NOT TAKEN

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Introduction[1]

Decision trees

During each human life, a child starts with many possible destinations. He or she then makes decisions, and each decision more closely defines who the person is and what it is possible for the person to become. The choice of a vocation defines who a person is, as does the choice of a husband or wife. Often chance plays a role. The decision to take a holiday at a particular place may lead to a chance meeting with a life partner. In a human life, we can observe a treelike pattern, similar to the decision tree of a person traveling through a landscape. At each forking of the path, a decision has to be made, and that decision determines more and more closely the traveler's ultimate destination. Analogously, in a human life, a tree-like series of decisions or external influences more and more closely define the person's identity and destiny. Each decision is a positive step, since it helps to define a person's character. But there is sadness too. As we step forward on the road ahead, we must renounce all other possibilities. Although we might embrace our destiny, we sometimes think with regret on the road not taken, and wonder what might have been if we had chosen other paths.

Pathfinding

The 2014 Nobel Prize in Physiology or Medicine was shared by John O'Keefe, May-Britt Moser and Edvard Moser. They received the prize for discovering the histologically observable structures in the brains of mammals which are used to remember pathways, for example the pathway through a maze. Humans also have such structures in their brains.

We can find many other examples of pathfinging in our daily lives. For example, when we send a letter or package, the address defines its path. Read backwards, it tells us first the country to which it should be sent, then the city or town, then the street, then the house or building, and finally the occupant.

We can also recognize similar pathfinding in pattern abstraction, in computer memories, and in programs of the brain.

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[1] This book makes use of my previously published book chapters dealing with decision trees, but a considerable amount of new material has been added

The evolution of human languages

According to the famous linguistic scientist Noam Chomsky, the astonishing linguistic abilities of humans are qualitatively different from the far more limited abilities of other animals. Furthermore, Prof. Chomsky maintains that these abilities were not acquired gradually, over many hundreds of thousands of years, but rapidly - almost suddenly. We owe it to his high reputation as a scientist to ask how this could have happened. After all, Darwinian evolution usually proceeds very slowly, which many intermediate steps.

There are many cases where a single mutation seems to have produced duplication of a structure. For example, we sometimes see the birth of an animal with two heads, or supernumerary legs. In the light of Professor Chomsky's observations, we ought to investigate the possibility that a single mutation caused a duplication of the pathfinding neural networks studied by Edvard Moser, May-Britt Moser, and John O'Keefe. We can then imagine that one copy of this duplicated pathfinding neural network system was modified to serve as the basis of human languages, in which the classification of words is closely analogous to the tree-like branching choice-pathways of an animal finding its way through a forest or maze.

Existentialism

According to existentialist philosophy, a person's identity is gradually developed during the course of the person's life, by a series of events and decisions. These events or decisions form tree-like patterns (decision trees) similar to the classification trees which Linnaeus used to define relationships between living organisms. or the grammatical classification trees in languages. We see this reflected in Jean-Paul Sartre's famous maxim, "Existence is prior to essence".

Positional number systems

In the decimal system, we start by asking: How many times does the number contain $10^0 = 1$? Then we ask: How many times does the number contain $10^1 = 10$? The next step is to ask: How many times does the number contain $10^2 = 100$, and so on. Continuing in this way, we can obtain a decimal representation of any non-negative integer, no matter how large it is. We can recognize here a decision tree of the same kind that Linnaeus used to classify living organisms.

Had we been using a base-2 (binary) representation, the decision tree would have been as follows: We would first have asked: How many times does the number contain $2^0 = 1$?; then How many times does it contain $2^1 = 2$?; then How many times does it contain $2^2 = 4$?, and so on. For example the number which is written as 65 in the decimal system becomes 100001 is the binary system. It contains 1×2^6, 1×10^0, and 0 times all other powers of 2. The number written as 66 in the decimal system becomes 100010 in the binary system, while 67 becomes 100011, and 68 is represented by 100100.

The history of computers

If civilization survives, historians in the distant future will undoubtedly regard the invention of computers as one of the most important steps in human cultural evolution - as important as the invention of writing or the invention of printing. The possibilities of artificial intelligence have barely begun to be explored, but already the impact of computers on society is enormous.

The Internet has changed our lives completely. It is interesting to notice that the Internet is based on a package address system, and hence on decision trees. In fact, decision trees play an important role in many aspects of computing, for example the organization of computer memories.

The mechanism of cell differentiation

An embryonic stem cell is like a child at birth. The child's destiny is not yet determined. All possibilities are open. As the child grows to be an adolescent and later an adult, his or her identity becomes gradually more and more closely defined. Choices and events begin to restrict the range of possibilities, and the person's identity becomes more and more clear. In a closely analogous way, in the growing embryo, the cell's identity becomes progressively more and more closely defined. In both the case of the person and that of the cell, we can recognize the operation of decision trees, like those of Linnaeus, or those of grammatical classification in languages.

Can the mechanism of cell differentiation be understood in terms of molecular biology? The final chapter of this book points to some answers.

Contents

Chapter 1

DECISION TREES

1.1 Robert Frost's message

The Road Not Taken

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;
Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,
And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.
I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I-
I took the one less traveled by,
And that has made all the difference.

An existentialist poem

During each human life, a child starts with many possible destinations. He or she then makes decisions, and each decision more closely defines who the person is and what it is possible for the person to become. The choice of a vocation defines who a person is, as does the choice of a husband or wife. Often chance plays a role. The decision to take a holiday at a particular place may lead to a chance meeting with a life partner. In a human life, we can observe a treelike pattern, similar to the decision tree of a person traveling through a landscape. At each forking of the path, a decision has to be made, and that decision determines more and more closely the traveler's ultimate destination. Analogously, in a human life, a tree-like series of decisions or external influences more and more closely define the person's identity and destiny. Each decision is a positive step, since it helps to define a person's character. But there is sadness too. As we step forward on the road ahead, we must renounce all other possibilities. Although we might embrace our destiny, we sometimes think with regret on the road not taken, and wonder what might have been if we had chosen other paths.

Robert Frost points to this characteristic of our lives in his poem *The Road Not Taken*, especially in the final lines,

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I-
I took the one less traveled by,
And that has made all the difference.

The existentialist philosophers also emphasized this characteristic of the human experience, starting with Søren Kierkegaard, whom we will discuss in more detail in Chapter 4. Jean-Paul Sartre coined the famous phrase, "Existence is prior to essence", which means that we gradually take on our identity through the many decisions and events that we encounter in our existence.

In Robert Frost's own life, the decision of his grandfather to buy a farm for Frost and his wife had a profound influence on Frost's identity as a poet. We associate his writing with descriptions of rural life in New England, and the period which he spent on the farm donated by his grandfather was thus crucial to his writing.

Robert Frost received the Pulitzer Prize for Poetry four times, more than any other person. He was nominated for the Nobel Prize in Literature 31 times, but never received it.

Figure 1.1: **Robert Frost (1874-1963), seen here in a photograph from 1910. In *The Road Not Taken*, as in many of his poems, Frost seems to be describing a concrete scene or experience, but at the end, the reader realizes that he has been aiming at something larger - he wants to tell us a universal truth about the human experience.**

Figure 1.2: **First line - on a building in Leiden.**

Figure 1.3: **The Robert Frost Farm in Derry, New Hampshire, where he wrote many of his poems.**

Figure 1.4: **U.S stamp, 1974.**

1.2 What are decision trees?

In this book, we will discuss what might be called decision trees. An example of such a tree is the address that we write on a postal package. Read backwards, the address first tells us the country to which the package is to be sent. Then comes the city or town; then the street; then the number of the building on the street, and finally the name of the person to whom the package should be delivered. We see the decision tree defining progressively more and more closely the destination of the package, just as in a human life, the decision tree defines progressively more and more closely the person's destination and identity.

Today our lives have been completely changed by the Internet. It is interesting to notice that the Internet sends packages of information using an address system identical to the one that our post offices use to send packages of Christmas presents. This is not the only role that decision trees play in our world of cyberspace. Indeed, all aspects of computers use decision trees. One suspects that when the human brain is better understood, it will be seen that decision trees within the brain play a central role in thought. The famous physiologist J.Z. Young made detailed experimental studies of decision trees within the octopus brain, as is discussed in Chapter 2.

As children, many of us have played the game, "20 Questions". In this game, someone thinks of a word. Then the other players try to guess the word by asking questions, to which the answer can only be "yes" or "no". Only 20 questions are allowed, but the word is almost always found correctly with this number of questions or less. This may seem surprising, unless we happen to know that $2^{20} = 1,048,576$, whereas the Second Edition of the 20-volume Oxford English Dictionary contains full entries for only 171,476 words in current use. Thus, one example of decision trees can be found in classification.

1.3 Linnaean classification of living organisms

During the 17th and 18th centuries, naturalists had been gathering information on thousands of species of plants and animals. This huge, undigested heap of information was put into some order by the great Swedish naturalist, Carl von Linné (1707-1778), who is usually called by his Latin name, Carolus Linnaeus.

Linnaeus was the son of a Swedish pastor. Even as a young boy, he was fond of botany, and after medical studies at Lund, he became a lecturer in botany at the University of Uppsala, near Stockholm. In 1732, the 25-year-old Linnaeus was asked by his university to visit Lapland to study the plants in that remote northern region of Sweden.

Linnaeus travelled four thousand six hundred miles in Lapland, and he discovered more than a hundred new plant species. In 1735, he published his famous book, *Systema Naturae*, in which he introduced a method for the classification of all living things.

Linnaeus not only arranged closely related species into genera, but he also grouped related genera into classes, and related classes into orders. (Later the French naturalist Cuvier (1769-1832) extended this system by grouping related orders into phyla.) Linnaeus introduced the binomial nomenclature, still used today, in which each plant or animal is

Figure 1.5: **The great Swedish naturalist Carolus Linnaeus developed a language which is now universally used for biological classification.**

given a name whose second part denotes the species while the first part denotes the genus.

Linneaus proposed three kingdoms, which were divided into classes. From classes, the groups were further divided into orders, families, genera (singular: genus), and species. An additional rank beneath species distinguished between highly similar organisms. While his system of classifying minerals has been discarded, a modified version of the Linnaean classification system is still used to identify and categorize animals and plants.

Although he started a line of study which led inevitably to the theory of evolution, Linnaeus himself believed that species are immutable. He adhered to the then-conventional view that each species had been independently and miraculously created six thousand years ago, as described in the Book of Genesis.

Linnaeus did not attempt to explain why the different species within a genus resemble each other, nor why certain genera are related and can be grouped into classes, etc. It was not until a century later that these resemblances were understood as true family likenesses, so that the resemblance between a cat and a lion came to be understood in terms of their descent from a common ancestor[1].

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[1] Linnaeus was to Darwin what Kepler was to Newton. Kepler accurately described the motions of the solar system, but it remained for Newton to explain the underlying dynamical mechanism. Similarly, Linnaeus set forth a descriptive "family tree" of living things, but Darwin discovered the dynamic mechanism that underlies the observations.

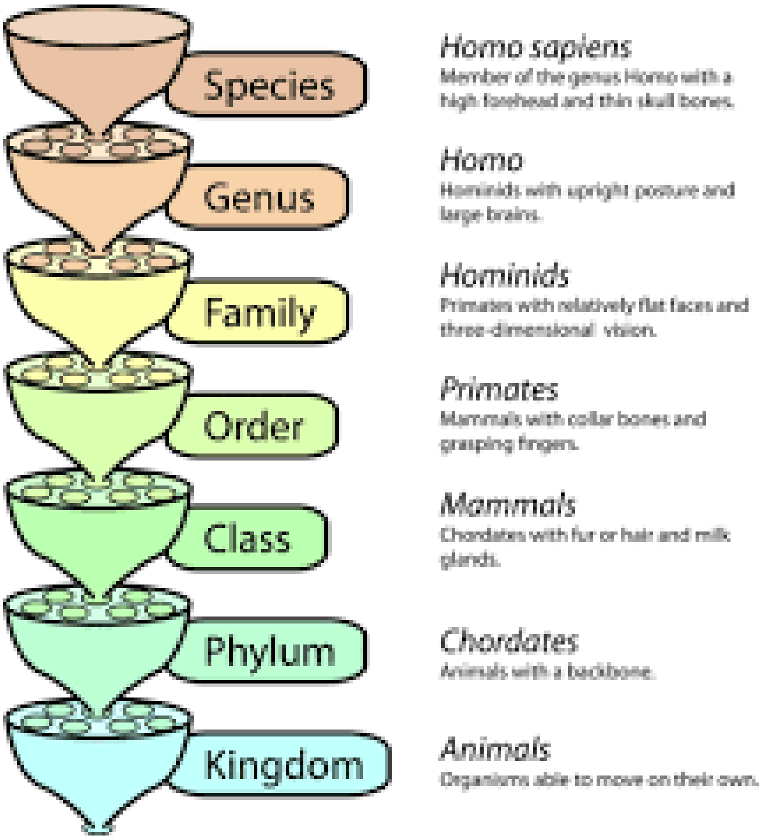


Figure 1.6: **The branching decision-trees in the Linnaean language of classification resembles the decision-trees in package-address systems such as postal systems of the Internet. Similar decision-trees are found when an animal finds its way through forest or maze.**

Figure 1.7: **Within the Animal kingdom, the polar bear belongs to the phylum Chordata, the class Mammalian, the order Carnivore, the family Ursidia, the genus Ursus, and the species Ursus arctus.**

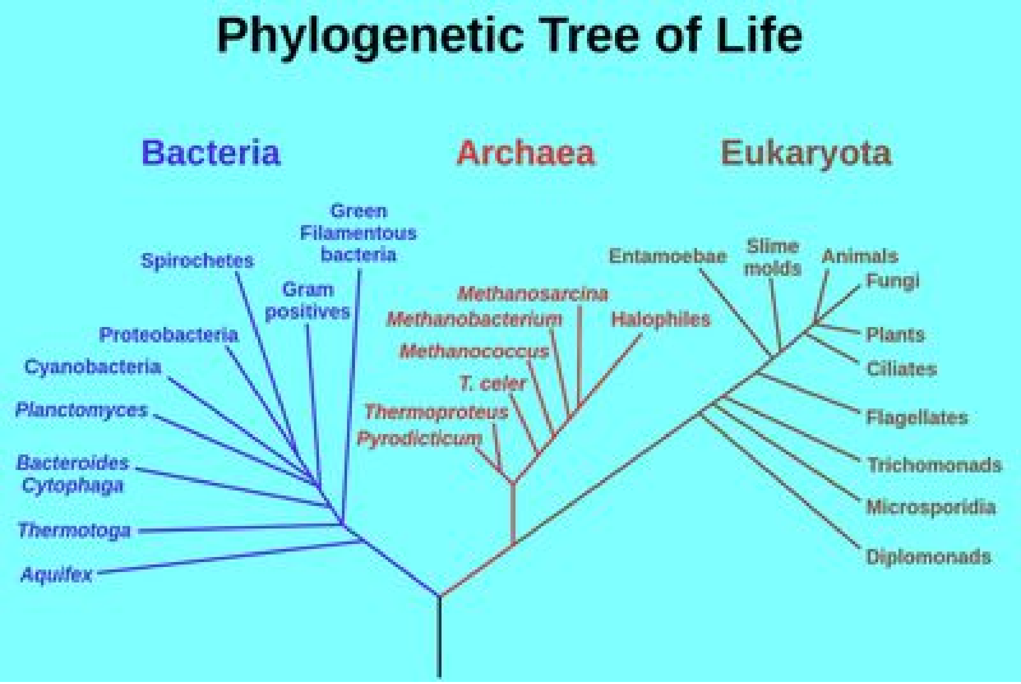


Figure 1.8: **The three-domain system currently used to classify living organisms. Within each domain, the classification becomes progressively finer: From classes, the groups were further divided into orders, families, genera (singular: genus), and species. An additional rank beneath species distinguished between highly similar organisms. While his system of classifying minerals has been discarded, a modified version of the Linnaean classification system is still used to identify and categorize animals and plants.**

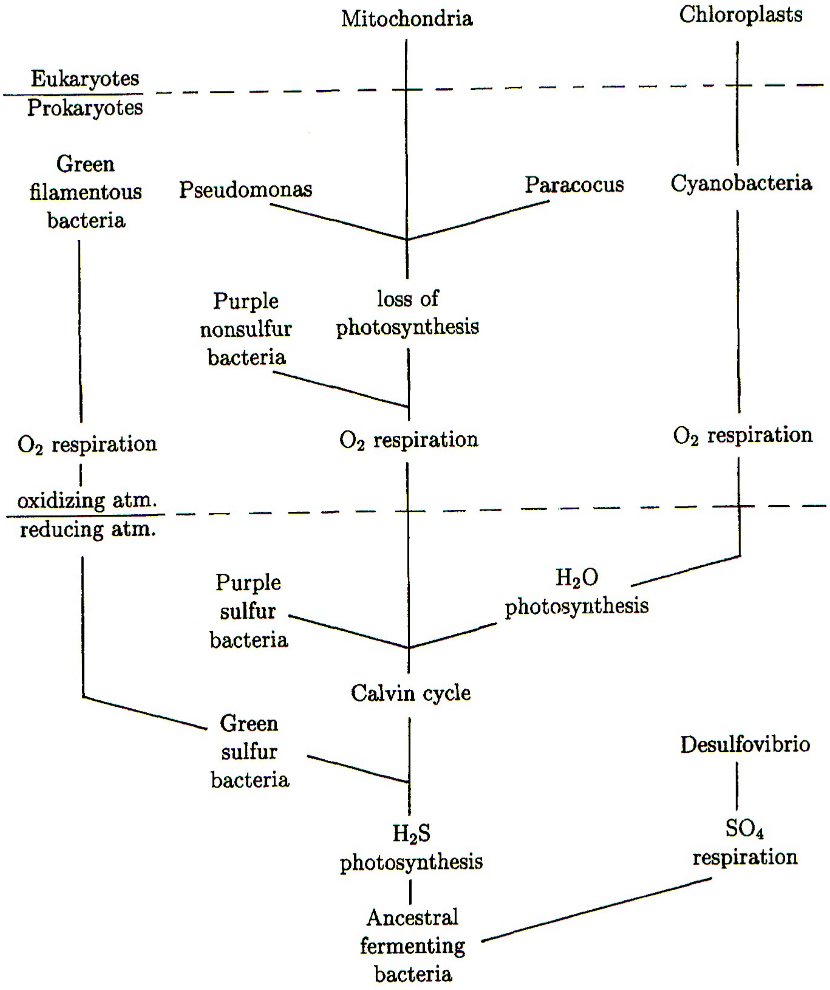


Figure 1.9: **Evolutionary relationships established by Dickerson and coworkers by comparing the amino acid sequences of Cytochrome C from various species.**

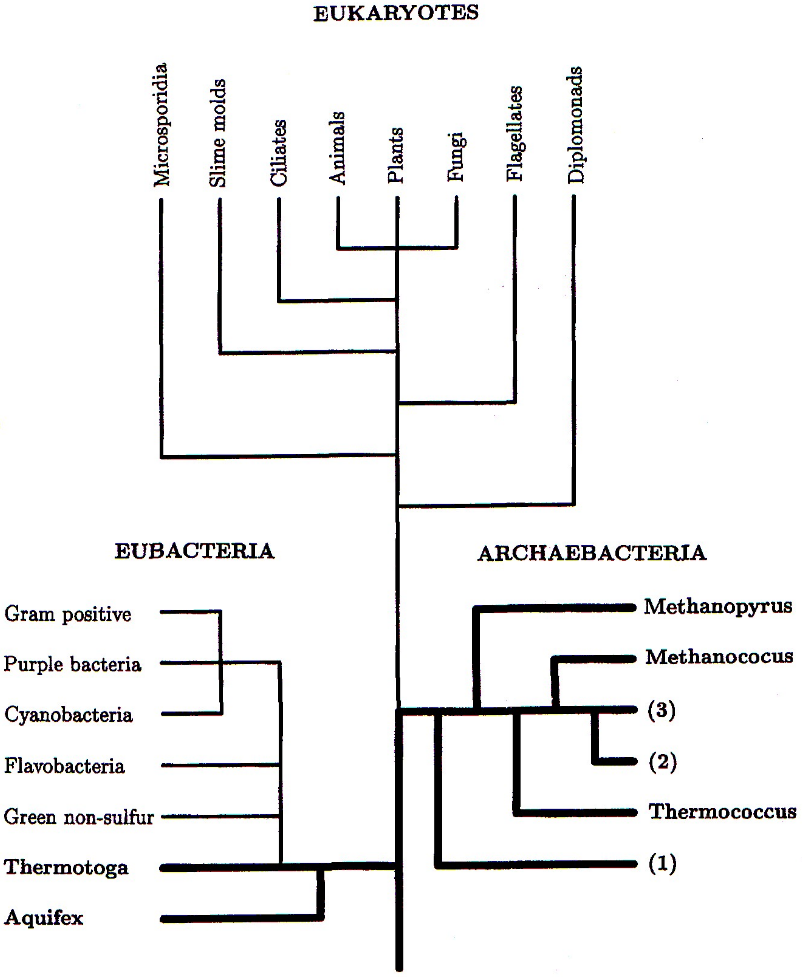


Figure 1.10: **This figure shows the universal phylogenetic tree, established by the work of Woese, Iwabe et al. Hyperthermophiles are indicated by bold lines and by bold type.**

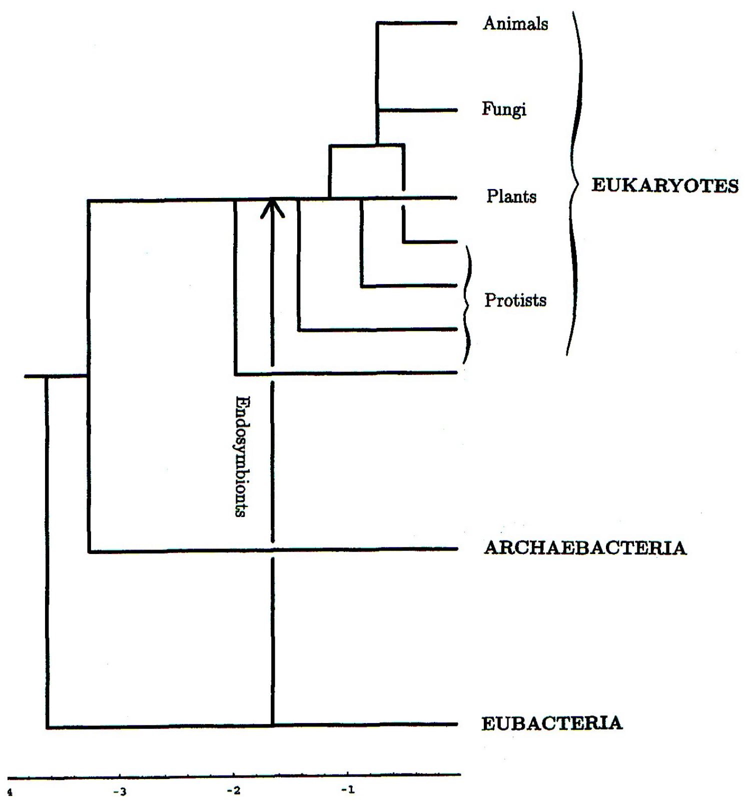


Figure 1.11: **Branching of the universal phylogenetic tree as a function of time. "Protists" are unicellular eukaryotes.**

Kingdoms and classes

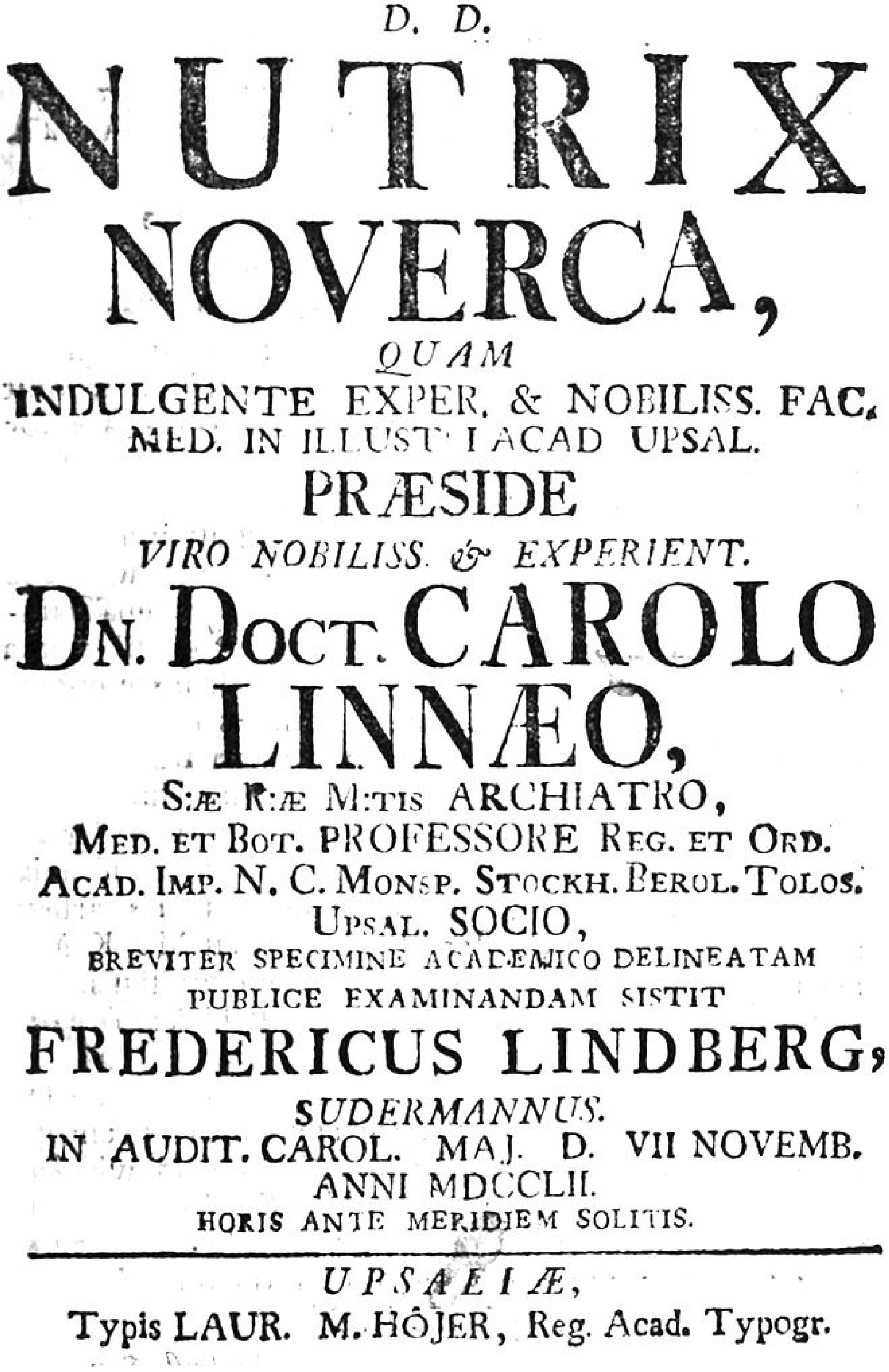
Animals

1. Mammalian (mammals)
2. Aves (birds)
3. Amphibia (amphibians)
4. Pisces (fish)
5. Insecta (insects)
6. Vermes (worms)

Plants

1. Monandria: flowers with 1 stamen
2. Diandria: flowers with 2 stamens
3. Triandria: flowers with 3 stamens
4. Tetrandria: flowers with 4 stamens
5. Pentandria: flowers with 5 stamens
6. Hexandria: flowers with 6 stamens
7. Heptandria: flowers with 7 stamens
8. Octandria: flowers with 8 stamens
9. Enneandria: flowers with 9 stamens
10. Decandria: flowers with 10 stamens
11. Dodecandria: flowers with 12 stamens
12. Icosandria: flowers with 20 (or more) stamens
13. Polyandria: flowers with many stamens
14. Didynamia: flowers with 4 stamens, 2 long and 2 short
15. Tetradynamia: flowers with 6 stamens, 4 long and 2 short
16. Monadelphia; flowers with the anthers separate, but the filaments united at the base
17. Diadelphia; flowers with the stamens united in two groups
18. Polyadelphia; flowers with the stamens united in several groups
19. Syngenesia; flowers with 5 stamens having anthers united at the edges
20. Gynandria; flowers having stamens united to the pistils
21. Monoecia: monoecious plants
22. Dioecia: dioecious plants
23. Polygamia: polygamodioecious plants
24. Cryptogamia: organisms that resemble plants but don't have flowers, which included fungi, algae, ferns, and bryophytes

Figure 1.12: **Wedding portrait of Linnaeus.**



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NUTRIX
NOVERCA,
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INDULGENTE EXPER. & NOBILISS. FAC.
MED. IN ILLUST. ACAD. UPSAL.
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VIRO NOBILISS. & EXPERIENT.
Dn. Doct. CAROLO
LINNÆO,
S:æ R:æ M:tis ARCHIATRO,
Med. et Bot. PROFESSORE Reg. et Ord.
Acad. Imp. N. C. Monsp. Stockh. Berol. Tolos.
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BREVITER SPECIMINE ACADEMICO DELINEATAM
PUBLICE EXAMINANDAM SISTIT
FREDERICUS LINDBERG,
SUDERMANNUS.
IN AUDIT. CAROL. MAJ. D. VII NOVEMB.
ANNI MDCCLII.
HORIS ANTE MERIDIEM SOLITIS.

UPSALIÆ,
Typis LAUR. M. HÔJER, Reg. Acad. Typogr.

Figure 1.13: **Cover of Nutrix Noverca (1752).**

1.4 Languages and classification

The binomial nomenclature introduced by Linnaeus is a language of classification. We can also recognize classification and decision trees in ordinary human languages, such as English, French or German. First of all, words are classified into broad categories as parts of speech: Is the word a noun, or is it a pronoun, an adjective, a verb, an adverb, a conjunction or an interjection? Then comes a finer classification: For example, if the word is a verb, is it transitive, intransitive or is it and auxiliary verb; and so on. In the classification of words, just as in the classification of living organisms, we can see decision trees at work.

Nouns

Proper nouns (too numerous to be listed here)

People's names and titles

Names for deity, religions, religious followers, and sacred books

Races, nationalities, tribes, and languages

Specific Places like countries, cities, bodies of water, streets, buildings, and parks

Specific organizations

Days of the week, months, and holidays

Brand names of products

Historical periods, well-known events, and documents

Titles of publications and written documents

Common nouns

Living organisms

1. Vegetable

    (a) tree (Eng.); Baum (Ger.); arbre (Fr.)
    (b) flower (Eng.); Blume (Ger.); fleur (Fr.)
    (c) srub (Eng.); Strauch (Ger.); arbuste (Fr.)
    (d) grass (Eng.); Gras (Ger.); herbe (Fr.)
    (e) bush (Eng.); Busch (Ger.); buisson (Fr.)
    (f) agricultural crop (Eng.); Landwirtschaft (Ger.); surgir (Fr.)
    (g) algae (Eng.); Algen (Ger.); algues (Fr.)
    (h) plankton (Eng.); Plankton (Ger.); plancton (Fr.)

2. Animal

   (a) people (Eng.); Menschen (Ger.); gens (Fr.)
   (b) man (Eng.); Männer (Ger.); homme (Fr.)
   (c) woman (Eng.); Frau (Ger.); femme (Fr.)
   (d) family (Eng.); Familie (Ger.); famille (Fr.)
   (e) student (Eng.); Schüler (Ger.); étudiant (Fr.)
   (f) hand (Eng.); Hand (Ger.); main (Fr.)
   (g) mother (Eng.); Mutter (Ger.); mère (Fr.)
   (h) father (Eng.); Vater (Ger.); père (Fr.)

Nonliving things

1. Concrete

   (a) world (Eng.); Welt (Ger.); monde (Fr.)
   (b) school (Eng.); Schule (Ger.); école (Fr.)
   (c) state (Eng.); Bundesland (Ger.); état (Fr.)
   (d) country (Eng.); Land (Ger.); pays (Fr.)
   (e) government (Eng.); Regierung (Ger.); gouvernement (Fr.)
   (f) water (Eng.); Wasser (Ger.); eau (Fr.)
   (g) home (Eng.); heimat (Ger.); maison (Fr.)
   (h) room (Eng.); Zimmer (Ger.); chambre (Fr.)
   (i) money (Eng.); Geld (Ger.); argent (Fr.)

2. Abstract

   (a) time (Eng.); Zeit (Ger.); temps (Fr.)
   (b) year (Eng.); Jahr (Ger.); an (Fr.)
   (c) day (Eng.); Tag (Ger.); journée (Fr.)
   (d) way (Eng.); Weg (Ger.); facon (Fr.)
   (e) thing (Eng.); Ding (Ger.); chose (Fr.)
   (f) life (Eng.); Leben (Ger.); la vie (Fr.)
   (g) group (Eng.); Gruppe (Ger.); groupe (Fr.)
   (h) problem (Eng.); Problem (Ger.); problème (Fr.)
   (i) part (Eng.); Teil (Ger.); partie (Fr.)
   (j) place (Eng.); Ort (Ger.); endroit (Fr.)
   (k) case (Eng.); Fall (Ger.); cas (Fr.)
   (l) week (Eng.); Woche (Ger.); la semaine (Fr.)
   (m) company (Eng.); Unternehmen (Ger.); compagnie (Fr.)
   (n) system (Eng.); System (Ger.); système (Fr.)
   (o) question (Eng.); Frage (Ger.); question (Fr.)
   (p) number (Eng.); Nummer (Ger.); nombre (Fr.)
   (q) night (Eng.); Nacht (Ger.); nuit (Fr.)
   (r) point (Eng.); Punkt (Ger.); point (Fr.)
   (s) area (Eng.); Bereich (Ger.); région (Fr.)

Pronouns

Personal pronouns

Singular personal pronouns

1. I (Eng.); ich (Ger.); je (Fr.)
2. me (Eng.); mich (Ger.); moi (Fr.)
3. you (Eng.); Sie (Ger.); toi (Fr.)
4. she (Eng.); sie (Ger.); elle (Fr.)
5. her (Eng.); ihr (Ger.); sa (Fr.)
6. he (Eng.); er (Ger.); il (Fr.)
7. him (Eng.); ihm (Ger.); lui (Fr.)
8. it (Eng.); es (Ger.); il (Fr.)

Plural personal pronouns

1. we (Eng.); wir (Ger.); nous (Fr.)
2. us (Eng.); uns (Ger.); nous (Fr.)
3. you (Eng.); Sie (Ger.); vous (Fr.)
4. they (Eng.); Sie (Ger.); ils (Fr.)
5. them (Eng.); Sie (Ger.); leur (Fr.)

Possessive pronouns

Singular possessive pronouns

1. my (Eng.); meine (Ger.); mon (Fr.)
2. mine (Eng.); mein (Ger.); mien (Fr.)
3. your (Eng.); Ihre (Ger.); votre (Fr.)
4. yours (Eng.); deine (Ger.); le tiens (Fr.)
5. hers (Eng.); ihres (Ger.); la sienne (Fr.)
6. his (Eng.); seine (Ger.); le sien (Fr.)
7. its (Eng.); seine (Ger.); ses (Fr.)

Plural possessive pronouns

1. yours (Eng.); deine (Ger.); le tiens (Fr.)
2. ours (Eng.); unsere (Ger.); les notres (Fr.)
3. theirs (Eng.); ihre (Ger.); Thiers (Fr.)

Reflexive pronouns

Singular reflexive pronouns

1. myself (Eng.); mich selber (Ger.); moi même (Fr.)
2. yourself (Eng.); dich selber (Ger.); toi même (Fr.)
3. himself (Eng.); selbst (Ger.); lui-même (Fr.)
4. herself (Eng.); Sie selber (Ger.); se (Fr.)
5. itself (Eng.); selbst (Ger.); même (Fr.)

Plural reflexive pronouns

1. ourselves (Eng.); uns selbst (Ger.); nous-mêmes (Fr.)
2. yourselves (Eng.); euch (Ger.); vous-mêmes (Fr.)
3. themselves (Eng.); sich (Ger.); se (Fr.)

Reciprocal pronouns

1. each other (Eng.); gegenseitig (Ger.); l'un et l'autre (Fr.)
2. one another (Eng.); einander (Ger.); un autre (Fr.)

Indefinite pronouns

1. all (Eng.); alle (Ger.); tout (Fr.)
2. another (Eng.); ein anderer (Ger.); un autre (Fr.)
3. any (Eng.); irgendein (Ger.); tout (Fr.)
4. anybody (Eng.); irgenjemand (Ger.); n'importe qui (Fr.)
5. anyone (Eng.); jemand (Ger.); n'importe qui (Fr.)
6. anything (Eng.); etwas (Ger.); n'importe quoi (Fr.)
7. both (Eng.); beide (Ger.); tous les deux (Fr.)
8. each (Eng.); jede einselne (Ger.); chaque (Fr.)
9. either (Eng.); entweder (Ger.); non plus (Fr.)
10. everybody (Eng.); jeder (Ger.); tout le monde (Fr.)
11. everyone (Eng.); jeder (Ger.); toutes les personnes (Fr.)
12. everything (Eng.); alles (Ger.); tout (Fr.)
13. few (Eng.); wenige (Ger.); peu (Fr.)
14. many (Eng.); veile (Ger.); beaucoup (Fr.)
15. neither... nor (Eng.); weder... noch (Ger.); ni... ni (Fr.)
16. nobody (Eng.); niemand (Ger.); personne (Fr.)
17. none (Eng.); keiner (Ger.); aucun (Fr.)
18. no one (Eng.); Niemand (Ger.); personne (Fr.)
19. nothing (Eng.); nichts (Ger.); rien (Fr.)
20. one (Eng.); eine (Ger.); un (Fr.)
21. several (Eng.); mehrere (Ger.); nombreuses (Fr.)

22. some (Eng.); etwas (Ger.); certains (Fr.)
23. somebody (Eng.); jemand (Ger.); quelqu'un (Fr.)
24. someone (Eng.); jemand (Ger.); quelqu'un (Fr.)
25. something (Eng.); etwas (Ger.); quelque chose (Fr.)

Demonstrative pronouns

Singular demonstrative pronouns

1. this (Eng.); Dies (Ger.); ce (Fr.)
2. that (Eng.); dass (Ger.); cette (Fr.)

Plural demonstrative pronouns

1. these (Eng.); diese (Ger.); celles-ci (Fr.)
2. those (Eng.); jene (Ger.); ceux (Fr.)

Intrrogative pronouns

1. who (Eng.); wer (Ger.); qui (Fr.)
2. whom (Eng.); wem (Ger.); qui (Fr.)
3. which (Eng.); welche (Ger.); lequel (Fr.)
4. whose (Eng.); deren (Ger.); dont (Fr.)
5. that (Eng.); dass (Ger.); cette (Fr.)

Relative pronouns

1. whoever (Eng.); wer auch immer (Ger.); quiconque (Fr.)
2. whomever (Eng.); wer auch immer (Ger.); quiconque (Fr.)
3. whichever (Eng.); was auch immer (Ger.); selon (Fr.)

Adjectives

Opinion

1. good (Eng.) gut (Ger.) bon (Fr.)
2. great (Eng.) gross (Ger.) grand (Fr.)
3. other (Eng.) andere (Ger.) autre (Fr.)
4. different (Eng.) anders (Ger.) différent (Fr.)
5. important (Eng.) wichtig (Ger.) important (Fr.)
6. bad (Eng.) schlecht (Ger.) mauvais (Fr.)
7. real (Eng.) echt (Ger.) vrai (Fr.)
8. best (Eng.) beste (Ger.) meilleur (Fr.)
9. right (Eng.) recht (Ger.) bon (Fr.)
10. only (Eng.) einzige (Ger.) seulement (Fr.)
11. early (Eng.) frühe (Ger.) précoce (Fr.)
12. sure (Eng.) sichere (Ger.) sûr (Fr.)
13. able (Eng.) fähige (Ger.) capable (Fr.)
14. late (Eng.) späte (Ger.) tardif (Fr.)
15. hard (Eng.) harte (Ger.) dur (Fr.)
16. major (Eng.) grosse (Ger.) majeur (Fr.)
17. better (Eng.) bessere (Ger.) meilleur (Fr.)

Size

1. high (Eng.) hoch (Ger.) haut (Fr.)
2. big (Eng.) gross (Ger.) grand (Fr.)
3. small (Eng.) klein (Ger.) petit (Fr.)
4. large (Eng.) gross (Ger.) gros (Fr.)
5. long (Eng.) lange (Ger.) long (Fr.)
6. little (Eng.) wenig (Ger.) petit (Fr.)
7. low (Eng.) niedrig (Ger.) bas (Fr.)

Age

1. new (Eng.) neu (Ger.) nouveau (Fr.)
2. old (Eng.) alt (Ger.) vieux (Fr.)
3. young (Eng.) jung (Ger.) jeune (Fr.)

Color

1. black (Eng.) schwarz (Ger.) noir (Fr.)
2. white (Eng.) weiss (Ger.) blanc (Fr.)
3. red (Eng.) rot (Ger.) rouge (Fr.)

Origin

1. American (Eng.) amerikanisch (Ger.) américain (Fr.)
2. national (Eng.) national (Ger.) national (Fr.)
3. political (Eng.) politisch (Ger.) politique (Fr.)
4. social (Eng.) sozial (Ger.) social (Fr.)
5. public (Eng.) öffentliches (Ger.) public (Fr.)
6. human (Eng.) menschliche (Ger.) humain (Fr.)
7. local (Eng.) lokal (Ger.) local (Fr.)

Verbs

Main verbs

1. Transative main verbs
   - (a) say (Eng.); sagen (Ger.); dire (Fr.)
   - (b) make (Eng.); machen (Ger.); faire (Fr.)
   - (c) know (Eng.); wissen (Ger.); connaître (Fr.)
   - (d) think (Eng.); denken (Ger.); penser (Fr.)
   - (e) take (Eng.); nehmen (Ger.); prendre (Fr.)
   - (f) want (Eng.); wollen (Ger.); vouloir (Fr.)
   - (g) use (Eng.); benutzen (Ger.); utiliser (Fr.)
   - (h) find (Eng.); finden (Ger.); trouver (Fr.)
   - (i) give (Eng.); geben (Ger.); donner (Fr.)
   - (j) tell (Eng.); sagen (Ger.); dire (Fr.)
   - (k) ask (Eng.); Fragen (Ger.); demander (Fr.)
   - (l) feel (Eng.); fühlen (Ger.); ressentir (Fr.)
   - (m) put (Eng.); stellen (Ger.); mettre (Fr.)
   - (n) mean (Eng.); bedeuten (Ger.); vouloir dire (Fr.)
   - (o) keep (Eng.); behalten (Ger.); garder (Fr.)
   - (p) let (Eng.); lassen (Ger.); laisser (Fr.)
   - (q) seem (Eng.); scheinen (Ger.); sembler (Fr.)
   - (r) help (Eng.); helfen (Ger.); aider (Fr.)
   - (s) show (Eng.); zeigen (Ger.); montrer (Fr.)
   - (t) like (Eng.); mögen (Ger.); aimer (Fr.)
   - (u) believe (Eng.); glauben (Ger.); croire (Fr.)
   - (v) hold (Eng.); halten (Ger.); tenir (Fr.)
   - (w) write (Eng.); schreiben (Ger.); écrire (Fr.)
   - (x) provide (Eng.); bereitstellen (Ger.); fournir (Fr.)
2. Intransative main verbs
   - (a) look (Eng.); sehen (Ger.); regarder (Fr.)
   - (b) work (Eng.); denken (Ger.); travailler (Fr.)
   - (c) call (Eng.); anrufen (Ger.); appeler (Fr.)
   - (d) need (Eng.); benötigen (Ger.); avoir besoin (Fr.)
   - (e) become (Eng.); werden (Ger.); devenir (Fr.)
   - (f) leave (Eng.); verlassen (Ger.); partir (Fr.)

(g) turn (Eng.); drehen (Ger.); tourner (Fr.)
(h) start (Eng.); anfangen (Ger.); commencer (Fr.)
(i) play (Eng.); speilen (Ger.); jouer (Fr.)
(j) move (Eng.); bewegen (Ger.); bouger (Fr.)
(k) live (Eng.); leben (Ger.); vivre (Fr.)
(l) happen (Eng.); passieren (Ger.); se passer (Fr.)
(m) sit (Eng.); sitzen (Ger.); s'asseoir (Fr.)

Auxilliary verbs

1. be (Eng.); zu sein (Ger.); être (Fr.)
2. am (Eng.); bin (Ger.); suis (Fr.)
3. is (Eng.); ist (Ger.); est (Fr.)
4. are (Eng.); sind (Ger.); sont (Fr.)
5. was (Eng.); war (Ger.); était (Fr.)
6. were (Eng.); sind (Ger.); étaient (Fr.)
7. being (Eng.); sein (Ger.); étant (Fr.)
8. been (Eng.); gewesen sein (Ger.); été (Fr.)
9. should (Eng.); sollte (Ger.); devrait (Fr.)
10. could (Eng.); könnte (Ger.); pourrait (Fr.)
11. will (Eng.); wird (Ger.); sera (Fr.)
12. have (Eng.); haben (Ger.); avoir (Fr.)
13. has (Eng.); hat (Ger.); a (Fr.)
14. would (Eng.); würde (Ger.); aurait (Fr.)
15. might (Eng.); könnte (Ger.); pourrait (Fr.)
16. can (Eng.); kann (Ger.); pouvez (Fr.)
17. may (Eng.); kann (Ger.); peux (Fr.)
18. must (Eng.); muss (Ger.); doit (Fr.)
19. shall (Eng.); sollte (Ger.); doit (Fr.)
20. ought (to) (Eng.); sollte (Ger.); doit (Fr.)

Adverbs

Direction of action

1. up (Eng.) hinauf (Ger.) en haut (Fr.)
2. out (Eng.) aus (Ger.) en dehors (Fr.)
3. back (Eng.) zurück (Ger.) arriére (Fr.)
4. down (Eng.) unten (Ger.) (Fr.)
5. along (Eng.) an (Ger.) le long de (Fr.)
6. about (Eng.) herum (Ger.) sur (Fr.)
7. over (Eng.) hinüber (Ger.) sur (Fr.)

Place of action

1. in (Eng.) hinein (Ger.) dans (Fr.)
2. there (Eng.) dorthin (Ger.) là-bas (Fr.)
3. here (Eng.) hier hin (Ger.) ici (Fr.)
4. on (Eng.) weiter (Ger.) sur (Fr.)
5. where (Eng.) wo (Ger.) où (Fr.)

Qualifying the action

1. so (Eng.) damit (Ger.) alors (Fr.)
2. just (Eng.) einfach (Ger.) juste (Fr.)
3. how (Eng.) wie (Ger.) comment (Fr.)
4. more (Eng.) mehr (Ger.) plus (Fr.)
5. also (Eng.) auch (Ger.) aussi (Fr.)
6. well (Eng.) gut (Ger.) bien (Fr.)
7. only (Eng.) nur (Ger.) seulement (Fr.)
8. very (Eng.) sehr (Ger.) très (Fr.)
9. even (Eng.) sogar (Ger.) même (Fr.)
10. too (Eng.) auch (Ger.) (Fr.)
11. really (Eng.) wirklich (Ger.) vraiment (Fr.)
12. most (Eng.) am meisten (Ger.) les plus (Fr.)
13. why (Eng.) warum (Ger.) pourquoi (Fr.)
14. about (Eng.) darüber (Ger.) à propos de (Fr.)
15. only (Eng.) nur (Ger.) seulement (Fr.)

Speed of action

1. quickly (Eng.) schnell (Ger.) rapidement (Fr.)
2. slowly (Eng.) langsam (Ger.) lentement (Fr.)
3. frequently (Eng.) häufig (Ger.) fréquemment (Fr.)
4. seldom (Eng.) selten (Ger.) rarement (Fr.)

Time of action

1. when (Eng.) wann (Ger.) quand (Fr.)
2. now (Eng.) jetzt (Ger.) maintenant (Fr.)
3. then (Eng.) dann (Ger.) ensuite (Fr.)
4. still (Eng.) immer noch (Ger.) toujours (Fr.)
5. as (Eng.) wie (Ger.) comme (Fr.)
6. never (Eng.) niemals (Ger.) jamais (Fr.)
7. always (Eng.) immer (Ger.) toujours (Fr.)
8. again (Eng.) nochmals (Ger.) encore (Fr.)
9. today (Eng.) heute (Ger.) aujourd'hui (Fr.)

10. often (Eng.) oft (Ger.) souvent (Fr.)
11. later (Eng.) später (Ger.) plus tard (Fr.)
12. once (Eng.) einmal (Ger.) une fois (Fr.)

Conjunctions

Coordinating conjunctions

1. for (Eng.); für (Ger.); pour (Fr.)
2. and (Eng.); und (Ger.); et (Fr.)
3. nor (Eng.); noch (Ger.); ni (Fr.)
4. but (Eng.); aber (Ger.); mais (Fr.)
5. or (Eng.); oder (Ger.); ou (Fr.)
6. yet (Eng.); noch (Ger.); encore (Fr.)
7. so (Eng.); damit (Ger.); alors (Fr.)

Correlative conjunctions

1. both... and (Eng.); sowohl... und (Ger.); et (Fr.)
2. neither... nor (Eng.); weder... noch (Ger.); ni... ni (Fr.)
3. whether... or (Eng.); ob... oder (Ger.); si... ou (Fr.)
4. either... or (Eng.); entweder... oder (Ger.); soit... ou (Fr.)
5. not only... but also (Eng.); nicht nur... sondern auch (Ger.); pas seulement... mais aussi (Fr.)

Prepositions

1. about (Eng.); worüber (Ger.); sur (Fr.)
2. above (Eng.); über (Ger.); au dessus (Fr.)
3. across (Eng.); über (Ger.); à travers (Fr.)
4. after (Eng.); nach (Ger.); après (Fr.)
5. among (Eng.); unter (Ger.); parmi (Fr.)
6. around (Eng.); um (Ger.); autour (Fr.)
7. at (Eng.); beim (Ger.); à (Fr.)
8. before (Eng.); vor (Ger.); avant (Fr.)
9. behind (Eng.); hinter (Ger.); derrière (Fr.)
10. below (Eng.); unten (Ger.); au dessous de (Fr.)
11. beneath (Eng.); unter (Ger.); sous (Fr.)
12. beside (Eng.); neben (Ger.); à côtè de (Fr.)
13. between (Eng.); zwischen (Ger.); entre (Fr.)
14. by (Eng.); am (Ger.); par (Fr.)
15. down (Eng.); runter (Ger.); vers le bas (Fr.)

16. during (Eng.); während (Ger.); pendant (Fr.)
17. except (Eng.); ausser (Ger.); sauf (Fr.)
18. from (Eng.); von (Ger.); de (Fr.)
19. instead (Eng.); stattdessen (Ger.); au lieu (Fr.)
20. into (Eng.); in (Ger.); dans (Fr.)
21. like (Eng.); wie (Ger.); comme (Fr.)
22. of (Eng.); von (Ger.); de (Fr.)
23. on (Eng.); auf (Ger.); sur (Fr.)
24. in (Eng.); in (Ger.); dans (Fr.)
25. through (Eng.); durch (Ger.); par (Fr.)
26. to (Eng.); zu (Ger.); à (Fr.)
27. toward (Eng.); zum (Ger.); vers (Fr.)
28. off (Eng.); aus (Ger.); hors (Fr.)
29. over (Eng.); über (Ger.); plus de (Fr.)
30. since (Eng.); seit (Ger.); depuis (Fr.)
31. under (Eng.); unter (Ger.); en dessous de (Fr.)
32. with (Eng.); mit (Ger.); avec (Fr.)
33. without (Eng.); ohne (Ger.); sans (Fr.)

Interjections

1. Oh! (Eng.); Oh! (Ger.); Oh! (Fr.)
2. Wow! (Eng.); Beeindruckend! (Ger.); Hou la la! (Fr.)
3. Ouch! (Eng.); Autsch! (Ger.); Aie! (Fr.)
4. Oops! (Eng.); Hoppla! (Ger.); Oops! (Fr.)
5. Hey! (Eng.); Hallo! (Ger.); Hey! (Fr.)

Articles

1. the (Eng.); das (Ger.); la (Fr.)
2. a (Eng.); ein (Ger.); une (Fr.)
3. and (Eng.); und (Ger.); et (Fr.)
4. an (Eng.); ein (Ger.); un (Fr.)

1.5 Decision trees in computing

Decision trees are important for the operation of computers. For example, when we wish to find a particular subject on our own personal computes, we first click on a large general file where we think that the information is stored. Once within that file, we are offered a choice of subfiles, and we click on the subfile that we think contains the information the we desire. The we are offered a choice of subsub files within which we must decide. This is an example of a decision tree taking us from the general to the specific.

Suggestions for further reading

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7. Edmund Otis Hovey (1908). *The Bicentenary of the Birth of Carolus Linnaeus.* New York: New York Academy of Sciences.
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Chapter 2

PATHFINDING

2.1 The 2014 Nobel Prize in Medicine and Physiology

Some excerpts from Edvard L. Moser's Nobel lecture

"All three 2014 Nobel Prize winners in Physiology or Medicine stand on the shoulders of E.C. Tolman. Based on experiments on rats running in various types of mazes, Tolman suggested from the 1930s to the 1950s that animals form internal maps of the external environment. He referred to such maps as cognitive maps and considered them as mental knowledge structures in which information was stored according to its position in the environment (Tolman, 1948). In this sense, Tolman was not only one of the first cognitive psychologists but he also directly set the stage for studies of how space is represented in the brain. Tolman himself avoided any reference to neural structures and neural activity in his theories, which was understandable at a time when neither concepts nor methods had been developed for investigations at the brain-behaviour

Figure 2.1: **The three winners of the 2014 Nobel Prize in Physiology or Medicine**

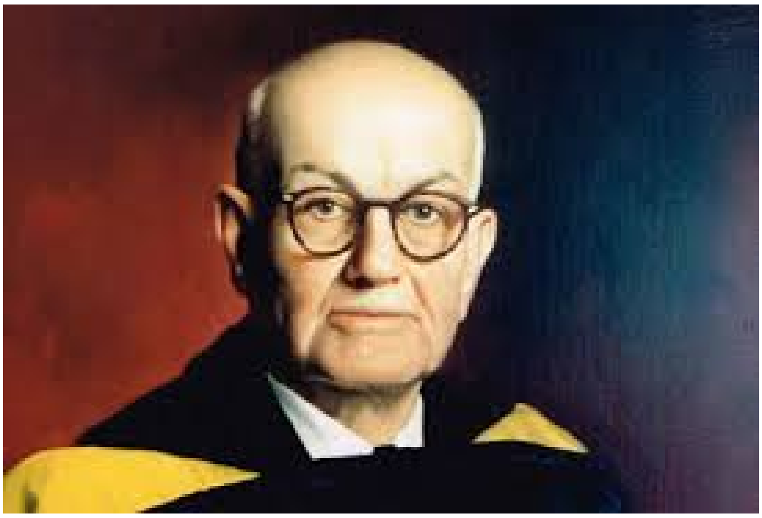

Figure 2.2: **Edward Chace Tolman (1886-1959). He founded a branch of psychology known as *perposive behaviourism.***

interface. However, at the end of his life he expressed strong hopes for a neuroscience of behaviour. In 1958, after the death of Lashley, he wrote the following in a letter to Donald O. Hebb when Hebb asked him about his view of physiological explanations of behaviour in the early days of behaviourism: “I certainly was an anti-physiologist at that time and am glad to be considered as one then. Today, however, I believe that this (‘physiologising’) is where the great new break-throughs are coming.”

“The psychology-physiology boundary was broken from the other side by two pioneers of physiology, David Hubel and Torsten Wiesel, who in the late 1950s bravely started to record activity from single neurons in the cortex, the origin of most of our intellectual activity. Inserting electrodes into the primary visual cortex of awake animals, they discovered how activity of individual neurons could be related to specific elements of the visual image. This work set the stage for decades of investigation of the neural basis for vision and helped the emergence of a new field of cortical computation. Their insights at the low levels of the visual cortex provided a window into how the cortex might work. As a result of Hubel and Wiesel’s work, parts of the coding mechanism for vision are now understood, almost 60 years after they started their investigations...

“The potential for understanding a higher brain function brought May-Britt and me to John O’Keefe’s lab in 1996. During a period of three months, John generously taught us everything about place cells and how they were studied and we then went back to Norway, to Trondheim, to set up our own new lab. One of our hopes was to find out how the place signal was generated.

“In this overview, I will first review the events that led up to the discovery of grid cells and the organization of a grid cell-based map of space in the medial

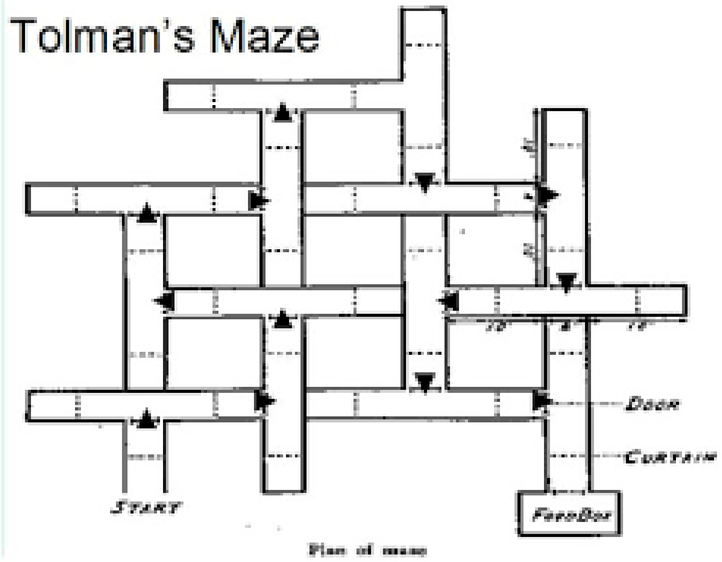

Figure 2.3: **Tolmen's experiments with animals learning to run through a maze form the foundation on which the work of John O'Keefe, May-Britt Moser and Edvard Moser was built.**

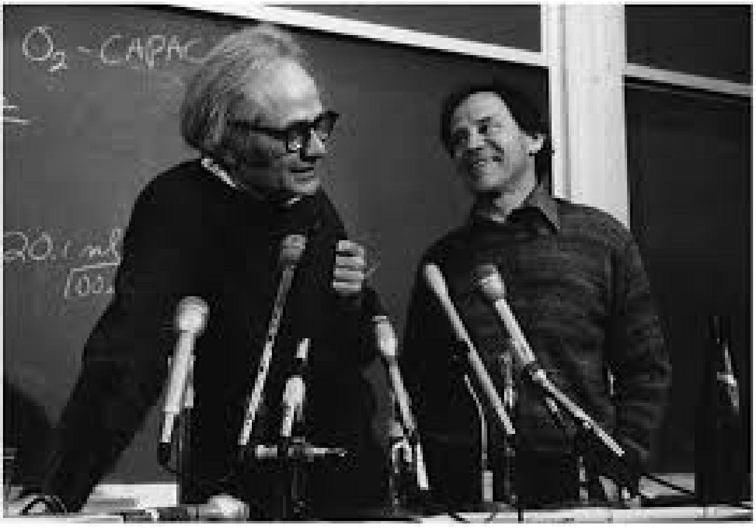

Figure 2.4: **David H. Hubel and Torsten N. Wiesel broke the physiology-psychology boundary from the physiology side. By identifying the elementary neural components of the visual image at low levels of the visual cortex, they showed that psychological concepts, such as sensation and perception, could be understood through elementary interactions between cells with specific functions.**

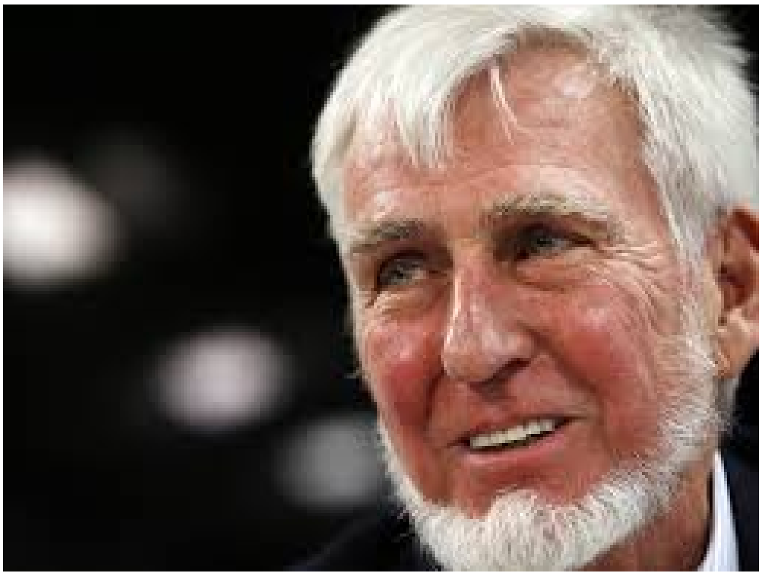

Figure 2.5: **A photo of John O'Keefe, who discovered place cells in the hippocampus. Place cells are cells that fire specifically when an animal is at a certain location in its local environment.**

entorhinal cortex. Then, in the second part, I will present recent work on the interactions between grid cells and the geometry of the external environment, the topography of the grid-cell map, and the mechanisms underlying the hexagonal symmetry of the grid cells.

To determine if place fields were formed in the intrahippocampal circuit, we worked together with neuroanatomist Menno Witter, then at the Free University of Amsterdam...

"In 2005, with our students Torkel Hafting, Marianne Fyhn and Sturla Molden, we were able to describe the structure of the firing pattern. Using larger environments than in the past, we could clearly see that the firing pattern was periodic. The multiple firing fields of the cell formed a hexagonal grid that tiled the entire surface space available to the animal, much like the holes in a bee hive or a Chinese checkerboard. Many entorhinal cells fired like this, and we named them grid cells. We were excited about the grid- like firing pattern, both because nothing like it exists in the sensory inputs to the animal, suggesting that the pattern is generated intrinsically in the entorhinal cortex or neighbouring structures, and because such a regular pattern provides a metric to the brain's spatial map, a metric that had been missing in the place map of the hippocampus."

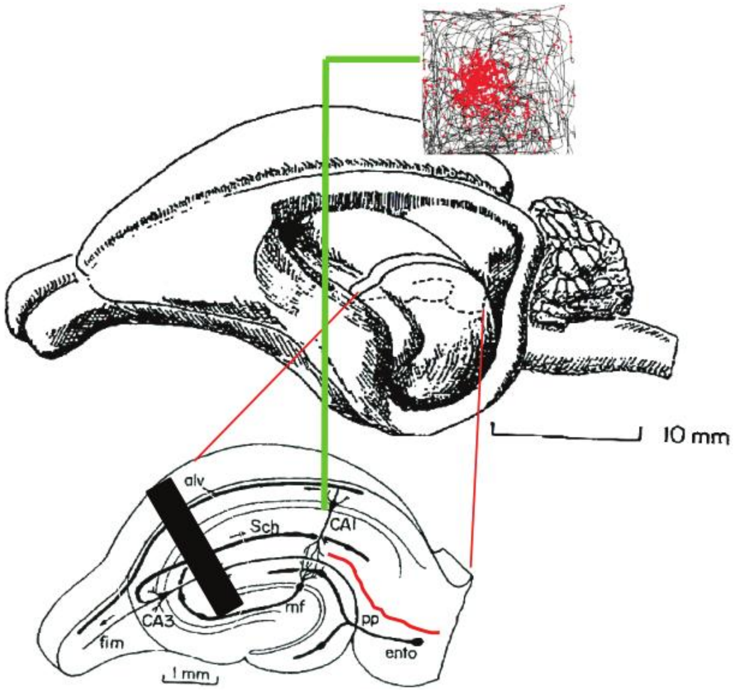

Figure 2.6: **Location of recording electrode and lesion in the experiment that led us to move out of the hippocampus, to the entorhinal cortex.**

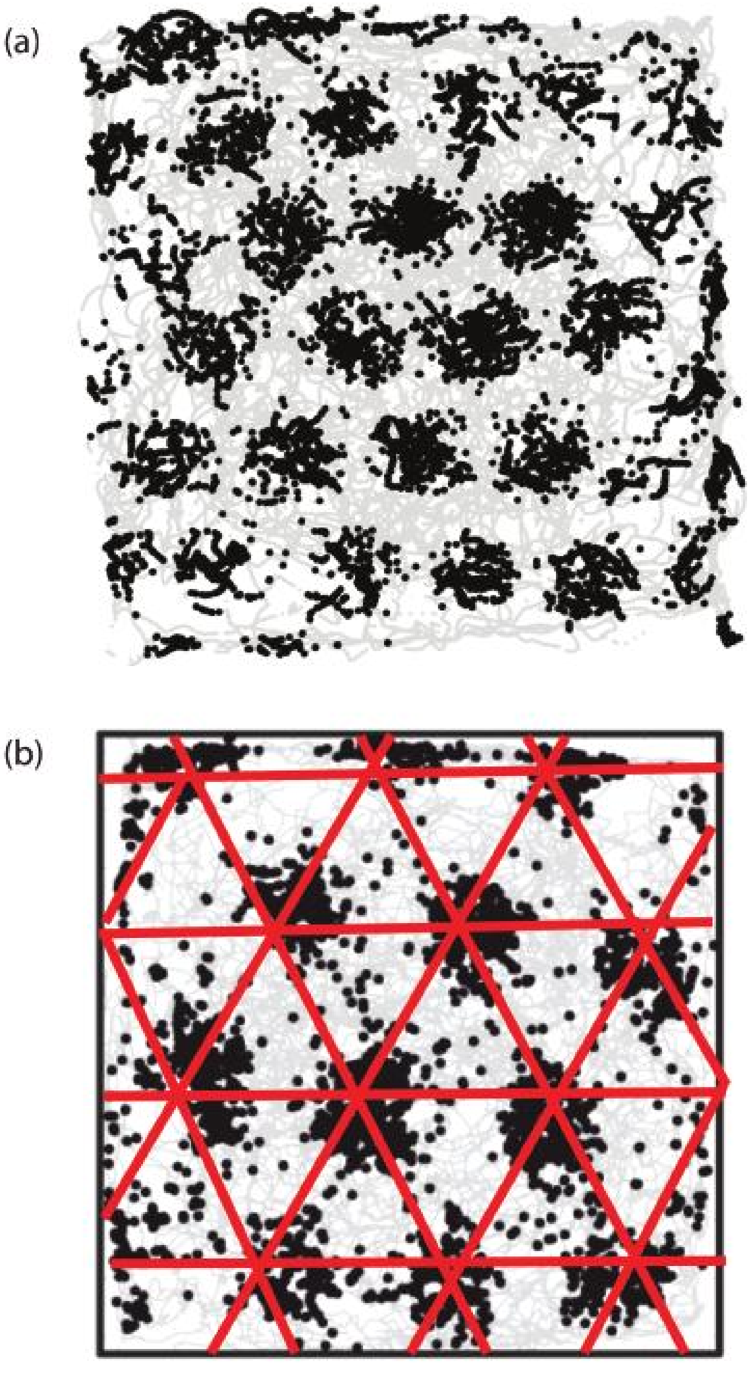

Figure 2.7: **Firing pattern of grid cells. (a) Spatially periodic firing pattern of an entorhinal grid cell during 30 min of foraging in a 220 cm wide square enclosure. The trajectory of the rat is shown in grey, individual spike locations in black. (b) Firing pattern of a grid cell in a 1 m wide enclosure. Symbols as in (a) but with red lines superimposed to indicate the hexagonal structure of the grid. Modified from Stensola et al. (2012) and Hafting et al. (2005), respectively.**

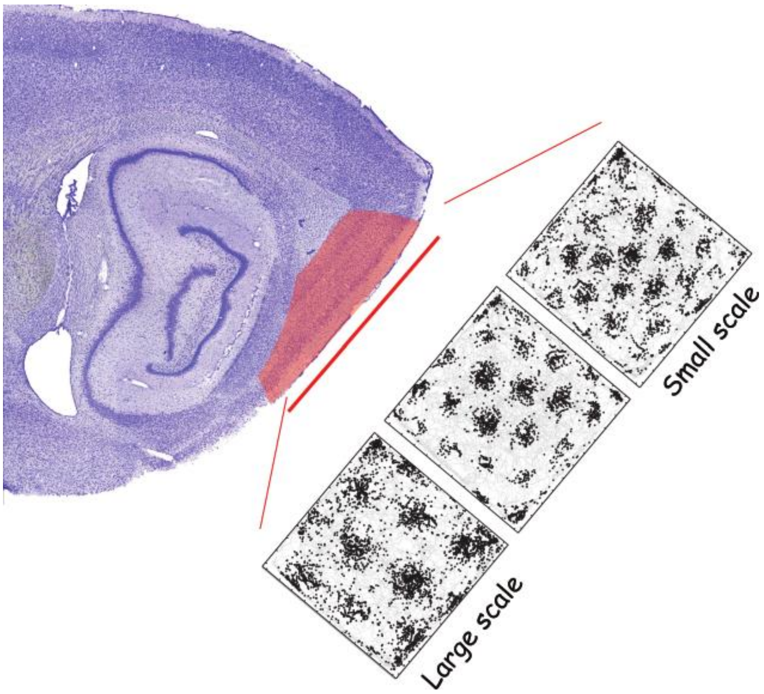

Figure 2.8: **Topographical organization of grid scale. The figure shows a sagittal brain section with medial entorhinal cortex indicated in red. Firing maps are shown for three grid cells recorded at successive dorso-ventral levels in medial entorhinal cortex. Note change from small scale to large scale along the dorso-ventral axis. Modified from Stensola et al. (2012).**

2.2 Paths in cell differentiation

In animals, the fertilized egg cell divides a number of times to form the blastula. At this stage of development, the cells are unspecialized. However, as they continue to divide, the cells become increasingly specialized. First they are totipotent, then pluripotent, then multipotent, then oligopotent and finally unipotent. The increasingly specialized differentiation of cells is closely analogous to the increasingly specialized classification of destinations in package address systems, which will be discussed in the next section.

2.3 Paths in package address systems

The history of the Internet and World Wide Web

The history of the Internet began in 1961, when Leonard Kleinrock, a student at MIT, submitted a proposal for Ph.D. thesis entitled "Information Flow in Large Communication Nets". In his statement of the problem, Kleinrock wrote: "The nets under consideration consist of nodes, connected to each other by links. The nodes receive, sort, store, and transmit messages that enter and leave via the links. The links consist of one-way channels, with fixed capacities. Among the typical systems which fit this description are the Post Office System, telegraph systems, and satellite communication systems." Kleinrock's theoretical treatment of package switching systems anticipated the construction of computer networks which would function on a principle analogous to a post office rather than a telephone exchange: In a telephone system, there is a direct connection between the sender and receiver of information. But in a package switching system, there is no such connection - only the addresses of the sender and receiver on the package of information, which makes its way from node to node until it reaches its destination.

Further contributions to the concept of package switching systems and distributed communications networks were made by J.C.R. Licklider and W. Clark of MIT in 1962, and by Paul Baran of the RAND corporation in 1964. Licklider visualized what he called a "Galactic Network", a globally interconnected network of computers which would allow social interactions and interchange of data and software throughout the world. The distributed computer communication network proposed by Baran was motivated by the desire to have a communication system that could survive a nuclear war. The Cold War had also provoked the foundation (in 1957) of the Advanced Research Projects Agency (ARPA) by the U.S. government as a response to the successful Russian satellite "Sputnik".

In 1969, a 4-node network was tested by ARPA. It connected computers at the University of California divisions at Los Angeles and Santa Barbara with computers at the Stanford Research Institute and the University of Utah. Describing this event, Leonard Kleinrock said in an interview: "We set up a telephone connection between us and the guys at SRI. We typed the L and we asked on the phone 'Do you see the L?' 'Yes we see the L', came the response. We typed the 0 and we asked 'Do you see the 0?' 'Yes we see the O.' Then we typed the G and the system crashed." The ARPANET (with 40 nodes) performed much better in 1972 at the Washington Hilton Hotel where the participants at a Conference on Computer Communications were invited to test it.

Although the creators of ARPANET visualized it as being used for long- distance computations involving several computers, they soon discovered that social interactions over the Internet would become equally important if not more so. An electronic mail system was introduced in the early 1970's, and in 1976 Queen Elizabeth II of the United Kingdom became one of the increasing number of e-mail users.

In September, 1973, Robert F. Kahn and Vinton Cerf presented the basic ideas of the Internet at a meeting of the International Network Working Group at the University Sussex in Brighton, England. Among these principles was the rule that the networks to be connected should not be changed internally. Another rule was that if a packet did not arrive at its destination, it would be retransmitted from its original source. No information was to be retained by the gateways used to connect networks; and finally there was to be no global control of the Internet at the operations level.

Computer networks devoted to academic applications were introduced in the 1970's and 1980's, both in England, the United States and Japan. The Joint Academic Network (JANET) in the U.K. had its counterpart in the National Science Foundation's network (NSFNET) in America and Japan's JUNET (Japan Unix Network). Internet traffic is approximately doubling each year,[1] and it is about to overtake voice communication in the volume of information transferred.

In March, 2011, there were more than two billion Internet users in the world. In North America they amounted to 78.3 % of the total population, in Europe 58.3 % and worldwide, 30.2 %. Another index that can give us an impression of the rate of growth of digital data generation and exchange is the "digital universe", which is defined to be the total volume of digital information that human information technology creates and duplicates in a year. In 2011 the digital universe reached 1.2 zettabytes, and it is projected to quadruple by 2015. A zettabyte is 10^{21} bytes, an almost unimaginable number, equivalent to the information contained in a thousand trillion books, enough books to make a pile that would stretch twenty billion kilometers.

Postal addresses

A second example of package address systems can be found in postal addresses. Here the coarsest category is country. Within a particular country the city or town is the next part of the address. Next, the street is specified; then the street number, and finally (in some cases), the number labeling the room or flat within a building. This progression from course categorization to progressively finer specification of the address can be seen in all types of classification.

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[1] In the period 1995-1996, the rate of increase was even faster - a doubling every four months

2.4 Paths in the organization of computer memories

Most of us use directories to organize the data on our computers. For example, on my own PC, the address of the file on which I am working at the moment is "home/work/books/languages". There is a directory called "home". Within "home" there are many sub-directories, one of which is called "work". Suppose that we click on "work". We find within this sub-directory many sub-sub-directories, one of which is called "books". If, among the many options, we click on "books", we find that it contains many sub-sub-sub-directories, one of which is called "languages".

We can visualize the process of starting in the home directory and finally reaching the sub-sub-sub-directory "languages" as a process of pathfinding. At each point where the paths branch, we make a choice, just as an animal does when finding its way through a forest or maze. At each choice, the destination reached becomes more specific; the classification of destinations becomes more refined.

One is reminded of the postal address system, within which the destination of a letter becomes more refined at each branch: First the country is specified, then the city or town, then the street, then the house number, and finally (in some cases) the apartment or room. Here too, the destination becomes progressively more refined as one progresses through a set of choices.

One may even be reminded of the existentialist philosophy of Jean-Paul Sartre and others, which has the motto "existence is prior to essence". As we progress through life, we make choices, and within each choice, we make sub-choices which define more and more specifically our final destination, i.e. our destiny or "essence".

Pattern abstraction in the octopus brain

J.Z. Young lectures to the Wells Society at Imperial College

I vividly remember a lecture that Prof. J.Z. Young delivered to the Wells Society[2] of London's Imperial College of Science and Technology. It was during the early 1960's, and at that time I was writing my Ph.D. thesis in theoretical chemistry.

Professor Young told us of his research on the visual cortex of the octopus. Being a mollusc, the octopus is lucky to have eyes at all, but in fact its eyes are very similar to our own, a striking example of convergent evolution. Young's research combined microscopic examination of extremely thin slices of the octopus brain with experiments on the extent to which the octopus is able to learn, and to profit from past experience.

Each image on the retina of the octopus eye is directly mapped in a one to one manner onto the outer layer of the animal's visual cortex. But as the signal propagated inwards towards the center of the visual cortex, the arrangement of dendrites and axons insures that synapses would only fire if activated by a specific pattern. The specificity of the pattern becomes progressively more refined as it propagates more deeply into the cortex.

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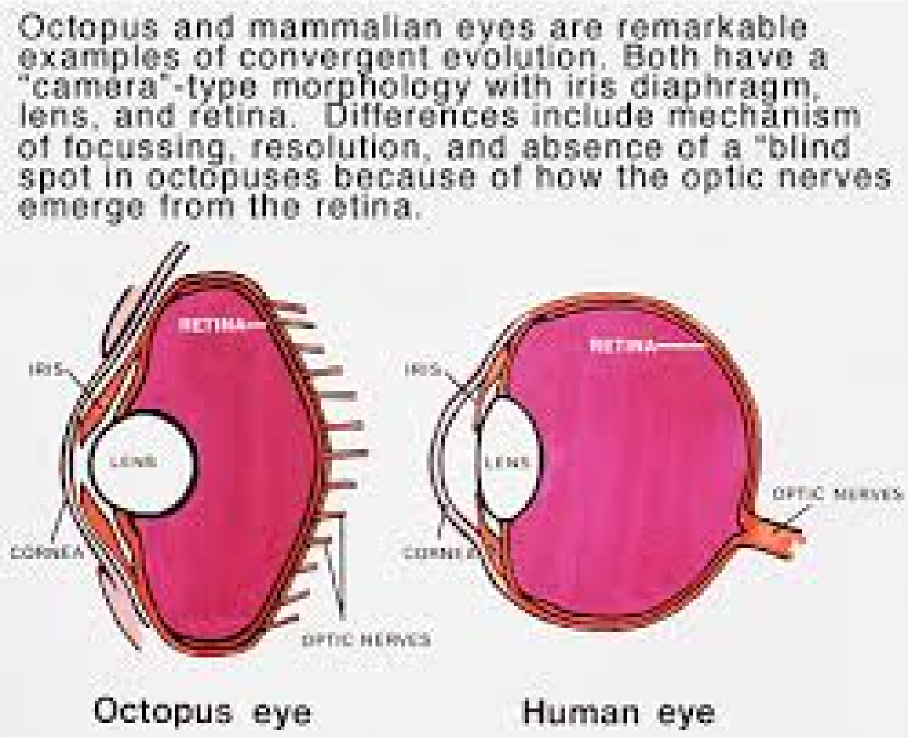
[2] H.G. Wells had once been a student at Imperial College, London. and the Wells Society was named after him.

Finally a “grandmother’s face cell” is reached, a cell which can only be activated by a specific pattern. At this point in the visual cortex of the octopus, neural pathways to to parts of the brain controlling muscular actions are activated. The paths branched, with one leading towards an attack response and the other towards retreat. There is a bias towards the attack pathway, so that initially, any pattern observed by the eyes of the animal will produce an attack.

Professor Young told us that he could actually see the arrangements of dendrites and axons in his histological studies of the visual cortex of the octopus. These histological studies were supplemented by behavioral experiments, in which the octopus was either rewarded for the attack, or else punished with a mild electric shock. If rewarded, the animal would continue to attack when again presented with the same pattern. If punished, the animal would always retreat when presented with the same stimulus. Prof. Young explained this behaviour by postulating the existence of a feedback neural circuit which blocked the attack pathway if the animal was punished. When the signal subsequently passed the “grandmother’s face cell”, only the retreat pathway remained. The octopus had learned.

Figure 2.9: **Prof. John Zachary Young, FRS, in 1978. He has been described as "one of the most influential biologists of the 20th century". His studies of pattern abstraction in the visual cortex of the octopus combined examination of histological microsections with experimental studies of octopus learning.**



Octopus and mammalian eyes are remarkable examples of convergent evolution. Both have a "camera"-type morphology with iris diaphragm, lens, and retina. Differences include mechanism of focussing, resolution, and absence of a "blind spot in octopuses because of how the optic nerves emerge from the retina.

Figure 2.10: **The octopus eye, like the human eye, has an image-forming lens and a retina. This similarity is a striking example of convergent evolution. The common ancestor of humans and molluscs had no eye at all.**

2.5 Abstraction of concepts and natural laws

Can two contradictory statements both be true? The physicist Niels Bohr thought that this could happen, and he called such an occurrence "complementarity". I think that I understand what Niels Bohr meant: Whenever we make a statement about the real world we are making a model which is simpler than what it is supposed to represent. Therefore every statement must to some extent be false because it is an oversimplification. In fact, a model of the world is an abstraction, and it is possible to make two conflicting abstractions, starting with the same real object.

If you say, "The eye is like a camera", you are making an abstraction by concentrating on the way that the eye works and the way that a camera works. Both use a lens to form an image. If you say "The eye is like a small onion", you are again making an abstraction, but this time concentrating the size and texture of the eye. It is somewhat round, elastic and damp. If you drop it on a stone floor, it will bounce rather than breaking. Both these abstractions have a certain degree of truth, although they are contradictory.

Similarly, science and ethics are both abstractions, and both oversimplify the real world, which is much more complex than either of them. Which abstraction we should use depends on the problem that we wish to discuss. If we are talking about atomic spectra, then Schrödinger and Dirac should be our guides. But if the lecture is on how to achieve peace in the world, I would far rather hear it from Mahatma Gandhi than from either Schrödinger or Dirac.

In his autobiography, Charles Darwin says that "Science consists in arranging facts in such a way that general conclusions may be drawn from them". At the lowest level of abstraction, we have a very large number of individual observations. A number of these observations may be gathered together to form a low-level generalization. The low-level generalizations may in turn be coordinated into a somewhat more general law, and so on. Today one hears that physicists are aiming at a "theory of everything", which, if could ever be achieved, would coordinate all individual observations of every kind.

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Chapter 3

THE EVOLUTION OF HUMAN LANGUAGES

Despite the impressive achievements of Koko, discussed in Chapter 3, one must conclude that human language abilities, with their enormous vocabularies and grammatical structures, are qualitatively different from animal languages. But what is the exact evolutionary history of human languages? Can this history be traced to specific mutations which are identifiable in the genomes of humans and homonids?

3.1 Chomsky's assertion of rapid change

Institute Professor Noam Chomsky of MIT, and more recently the University of Arizona, was born in 1928 in Philadelphia. Today he is considered to be the world's greatest public intellectual, and is famed as a linguist, philosopher, cognitive scientist, historian, social critic, and political activist. The author of more than 100 books, Prof. Chomsky has been called "the father of modern linguistics".

Noam Chomsky began studies at the University of Pennsylvania at the age of 16. His courses there included linguistics, mathematics, and philosophy.

The Wikipedia article on Prof. Chomsky states that "From 1951 to 1955 he was appointed to Harvard University's Society of Fellows, where he developed the theory of transformational grammar for which he was awarded his doctorate in 1955. That year he began teaching at MIT, in 1957 emerging as a significant figure in the field of linguistics for his landmark work Syntactic Structures, which remodeled the scientific study of language, while from 1958 to 1959 he was a National Science Foundation fellow at the Institute for Advanced Study. He is credited as the creator or co-creator of the universal grammar theory, the generative grammar theory, the Chomsky hierarchy, and the minimalist program.

"Since the 1960s, Chomsky has maintained that syntactic knowledge is at least partially inborn, implying that children need only learn certain parochial features of their native languages. Chomsky based his argument on observations about human language

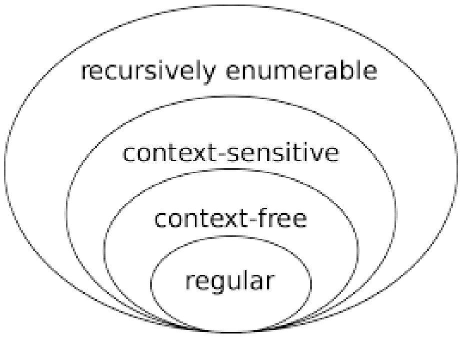

Figure 3.1: The Chomsky hierarchy. In the formal languages of computer science and linguistics, the Chomsky hierarchy is a containment hierarchy of classes of formal grammars. This hierarchy of grammars was described by Noam Chomsky in 1956. It is sometimes also called the Chomsky-Schützenberger hierarchy after Marcel-Paul Schützenberger, who played a crucial role in the development of the theory of formal languages.

acquisition, noting that there is an enormous gap between the linguistic stimuli to which children are exposed and the rich linguistic knowledge they attain (see: ‘poverty of the stimulus’ argument). For example, although children are exposed to only a finite subset of the allowable syntactic variants within their first language, they somehow acquire the ability to understand and produce an infinite number of sentences, including ones that have never before been uttered.

“To explain this, Chomsky reasoned that the primary linguistic data (PLD) must be supplemented by an innate linguistic capacity. Furthermore, while a human baby and a kitten are both capable of inductive reasoning, if they are exposed to exactly the same linguistic data, the human will always acquire the ability to understand and produce language, while the kitten will never acquire either ability.

“Chomsky labeled whatever relevant capacity the human has that the cat lacks as the language acquisition device (LAD), and he suggested that one of the tasks for linguistics should be to determine what the LAD is and what constraints it imposes on the range of possible human languages. The universal features that would result from these constraints constitute ‘universal grammar’.”

Figure 3.2: The world-famous linguist, Institute Professor Noam Chomsky, believes that human languages are qualitatively different from animal languages, and that humans acquired their amazing linguistic abilities very quickly. We need to examine the detailed molecular mechanisms by which this could have occurred, bearing in mind Gerrod's one-gene-one-protein hypothesis and Darwin's picture of evolution through many gradual steps. We also need to bear in mind Darwin's discussion of serial homologies.

3.2 Parse trees

A parse tree is an ordered, rooted tree that represents the syntactic structure of a string according to some context-free grammar.

1. S for sentence, the top-level structure in this example
2. NP for noun phrase. The first (leftmost) NP, a single noun "John", serves as the subject of the sentence. The second one is the object of the sentence.
3. VP for verb phrase, which serves as the predicate
4. V for verb. In this case, it's a transitive verb hit.
5. D for determiner, in this instance the definite article "the"
6. N for noun

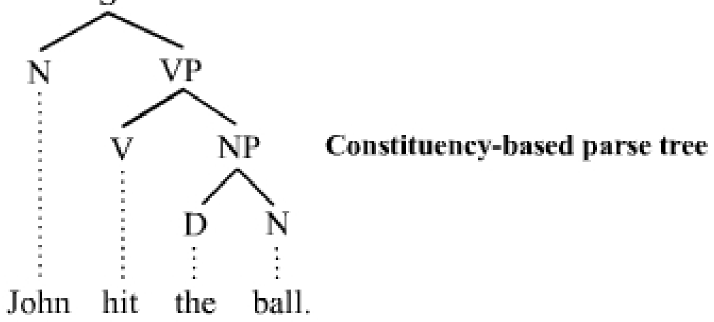

Figure 3.3: The tree-like structure of grammar in the parse tree analysis is analogous to the classification systems discussed in Chapter 5 (Pathfinding).

3.3 Garrod's hypothesis

In 1909, the English physician, Archibald Garrod, proposed a one-gene- one-protein hypothesis. He believed that hereditary diseases are due to the absence of specific enzymes. According to Garrod's hypothesis, damage suffered by a gene results in the faulty synthesis of the corresponding enzyme, and loss of the enzyme ultimately results in the symptoms of the hereditary disease.

In the 1940's, Garrod's hypothesis was confirmed by experiments on the mold, Neurospora, performed at Stanford University by George Beadle and Edward Tatum. They demonstrated that mutant strains of the mold would grow normally, provided that specific extra nutrients were added to their diets. The need for these dietary supplements could in every case be traced to the lack of a specific enzyme in the mutant strains. Linus Pauling later extended these ideas to human genetics by showing that the hereditary disease, sickle-cell anemia, is due to a defect in the biosynthesis of hemoglobin.

3.4 The FOXP2 gene and protein

Interestingly, a gene which seems to be closely associated with human speech has recently been located and mapped by C.S.L. Lai *et al*, who reported their results in Nature, **413**, 2001. These authors studied three generations of the "KE" family, 15 members of which are afflicted with a severe speech disorder. In all of the afflicted family members, a gene called FOXP2 on chromosome 7 is defective. In another unrelated individual, "CS", with a strikingly similar speech defect, the abnormality was produced by chromosomal translocation, the breakpoint coinciding exactly with the location of the FOXP2 gene.

A still more recent study of the FOXP2 gene was published online in Nature AOP on August 14, 2002. The authors (Wolfgang Enard, Molly Przeworski, Cecilia S.L. Lai, Victor Wiebe, Takashi Kitano, Anthony P. Monaco, and Svante Paabo) sequenced the FOXP2 gene and protein in the chimpanzee, gorilla, orang-utan, rhesus macaque and mouse, comparing the results with sequences of human FOXP2. They found that in the line from the common ancestor of mouse and man to the point where the human genome branches away from that of the chimp, there are many nucleotide substitutions, but all are silent, i.e. they have no effect at all on the FOXP2 protein. The even more numerous non-silent DNA mutations which must have taken place during this period seem to have been rejected by natural selection because of the importance of conserving the form of the protein. However, in the human line after the human-chimp fork, something dramatic happens: There are only two base changes, but both of them affect the protein! This circumstance suggests to Enard et al that the two alterations in the human FOXP2 protein conferred a strong evolutionary advantage, and they speculate that this advantage may have been an improved capacity for language.

The case of the FOXP2 gene and protein illustrates Gerrod's hypothesis: We see here the one-gene-one-protein hypothesis in action. A single mutation seems to have produced a severe speech and linguistic disorder in the "KE" family.

3.5 Slow evolutionary change; serial homologies

The fact each individual mutation affects a single gene, and hence the synthesis of a single protein, explains the gradual steps observed in evolution, first by Charles Darwin, and later by many other researchers. A mutation produces a small change in the morphology and functions of an organism, and the change is preserved if beneficial.

Gharles Darwin discussed serial homologies in *The Origin of Species*: “serial homologies”, - cases where symmetrically repeated parts of an ancient progenitor have been modified for special purposes in their descendants. For example, the bones which fit together to form the brain case in reptiles, birds and mammals can be seen in fossil sequences to be modified vertebrae of an ancient progenitor.

After discussing many examples, Darwin exclaims, “How inexplicable are these cases of serial homologies on the ordinary view of creation! Why should the brain be enclosed in a box composed of such numerous and extraordinarily-shaped pieces of bone?... Why should similar bones have been created to form the wing and leg of a bat, used as they are for totally different purposes, namely walking and flying? Why should one crustacean, which has an extremely complex mouth, formed of many parts, consequently have fewer legs; or conversely, those with many legs have simpler mouths? Why should the sepals, petals, stamens and pistils in each flower,though fitted for such distinct purposes, be all constructed on the same pattern?... On the theory of natural selection we can, to a certain extent, answer these questions.... An indefinite repetition of the same part is the common characteristic of all low or little-specialized forms... We have already seen that parts many times repeated are eminently liable to vary... Consequently such parts, being already present in considerable numbers, and being highly variable, would naturally afford materials for adaption to the most different purposes.”

There are many cases where a single mutation seems to have produced duplication of a structure. For example, we sometimes see the birth of an animal with two heads, or supernumerary legs. In the light of Professor Chomsky’s observation that human languages are qualitatively different from animal languages, and his belief that modern humans acquired their astonishing linguistic abilities very rapidly, we ought to investigate the possibility that a single mutation caused a duplication of the pathfinding neural networks studied by Edvard Moser, May-Britt Moser, and John O’Keefe. We can then imagine that one copy of this duplicated pathfinding neural network system was modified to serve as the basis of human languages, in which the classification of words is closely analogous to the tree-like branching choice-pathways of an animal finding its way through a forest or maze.[1]

How could we test such an hypothesis? Hopefully the methods of Svante Pääbo and his colleagues to sequence the genomes of ancient progenitors of humans may be able to provide us with answers.

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[1] Bold face is used here because this paragraph contains the central message of this book.

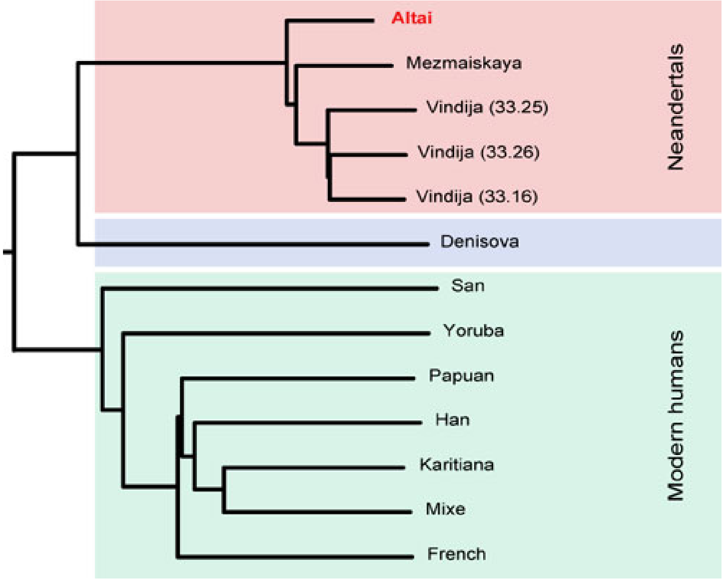

Figure 3.4: The family tree of Neanderthals, Denisovans and modern humans.

3.6 The Neanderthal and Denisovan genomes

Prof. Dr. Svante Pääbo and his colleagues at the Max Planck institute for Evolutionary Anthropology recently published a high-coverage genome of a Neanderthal. The genome was extracted from the bone fragment of a Neanderthal female from around 50,000-100,000 years ago, found in a cave in the Altai mountains of Siberia.[2]

Svante Pääbo and his colleagues were also able to find the complete genetic sequence of the Denisovans, an eastern cousin of the Neanderthals. One can hope that this brilliant work can be extended to even more ancient branches of the human family tree, perhaps even to Homo erectus. By working with genome differences between humans and their ancestors, paeleogeneticists may in the future be able to date the mutation or mutations that made human language qualitatively different from the languages of animals.

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[2] http://www.eva.mpg.de/neandertal/index.html

Figure 3.5: The Denisova cave in the Altai Mountains of Siberia was once the home of a hermit, Denis, and the cave takes its name from him. The photo shows tourists visiting the cave. It was here that scientists found the finger bone and tooth of a female homonid. The species, which they named Denisovan after the cave where the remains were found, proved to be the eastern cousins of the Neanderthals.

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Chapter 4

EXISTENTIALISM

According to existentialist philosophy, a person's identity is gradually developed during the course of the person's life, by a series of events and decisions. These events or decisions form tree-like patterns (decision trees) similar to the classification trees which Linnaeus used to define relationships between living organisms. or the grammatical classification trees in languages.

4.1 *Either - Or*

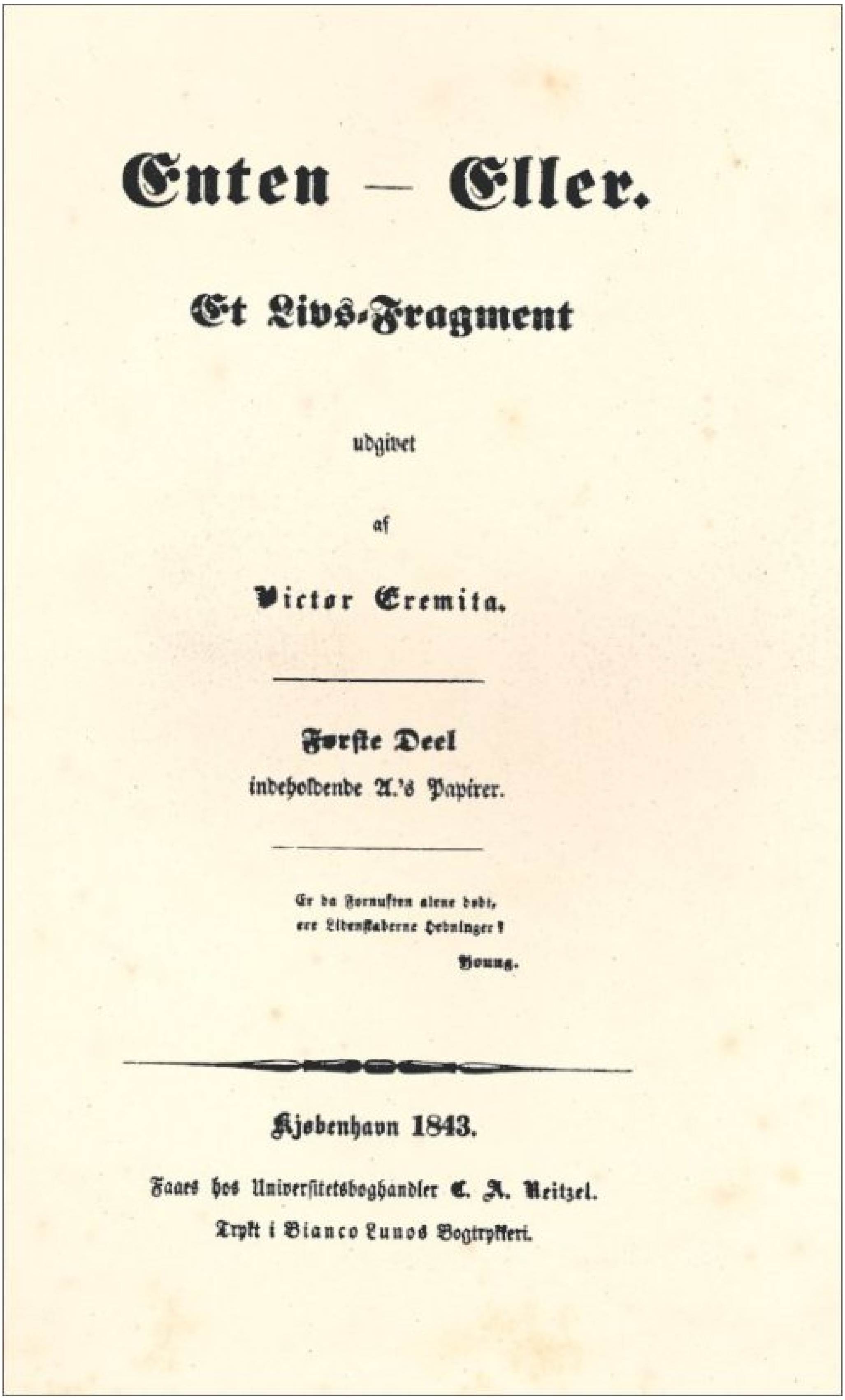
Søren Kierkegaard (1813-1855) was born into an affluent Copenhagen family, and educated at the University of Copenhagen, where he obtained a Master of Arts degree in 1841. During his short life, Kierkegaard published a large number of books on religion and philosophy. These books have established his reputation as the first important existentialist writer:

- Christian Discourses (Christelige Taler)
- The Concept of Anxiety (Begrebet Angest)
- The Concept of Irony (Om Begrebet Ironi)
- Concluding Unscientific Postscript (Afsluttende uvidenskabelig Efterskrift)
- The Crisis and A Crisis in the Life of an Actress (Krisen og en Krise i en Skuespillerindes Liv)
- Edifying Discourses in Diverse Spirits (Opbyggelige Taler i forskjellig Aand)
- Either/Or (Enten - Eller)
- Fear and Trembling (Frygt og Bæven)
- For Self-Examination: Recommended to the Present Age (Til Selvprøvelse. Samtiden anbefalet)
- Four Upbuilding Discourses (1843) (Fire opbyggelige Taler)
- Four Upbuilding Discourses (1844) (Fire opbyggelige Taler)
- From the Papers of One Still Living (Af en endnu Levendes Papirer)
- The Highpriest - The Publican - The Woman, which was a Sinner (Ypperstepræsten - Tolderen - Synderinden)

- Judge for Yourself! (Dømmer selv!)
- The Lilies of the Field and the Birds of the Air (Lilien paa Marken og Fuglen under Himlen)
- A Literary Announcement (En literair Anmeldelse)
- The Moment (Øieblikket)
- On my Work as an Author (Om min Forfatter-Virksomhed)
- Philosophical Fragments (Philosophiske Smuler)
- The Point of View of My Work as an Author (Synspunktet for min Forfatter-Virksomhed)
- Practice in Christianity (IndÃ¸velse i Christendom)
- Prefaces (Forord)
- Repetition (Gjentagelsen)
- The Sickness Unto Death (Sygdommen til Døden)
- Stages On Life's Way (Stadier paa Livets Vei)
- Three Discourses on Imagined Occasions (Tre Taler ved tænkte Leiligheder)
- Three Upbuilding Discourses (1843) (Tre opbyggelige Taler)
- Three Upbuilding Discourses (1844) (Tre opbyggelige Taler)
- Two Minor Ethico-Religious Treatises (Tvende ethisk-religieuse Smaa-Afhandlinger)
- Two Upbuilding Discourses (1843) (To opbyggelige Taler)
- Two Upbuilding Discourses (1844) (To opbyggelige Taler)
- Two Upbuilding Discourses at Friday Eucharist (To Taler ved Altergangen om Fredagen)
- An Upbuilding Discourse (1850) (En opbyggelig Tale)
- Works of Love (Kjerlighedens Gjerninger)

Figure 4.1: **A head-and-shoulders portrait sketch of Søren Kierkegaard as a young man in his twenties. The unfinished portrait was made by his cousin, Niels Christian Kierkegaard.**

Figure 4.2: **Regine Olsen (1822-1904), Kierkegaard's fiancée, She was a muse for his writings. He broke off the engagement in 1841. Although he mentioned that he thought that his "melancholy" made him unsuitable for marriage, his precise motives for breaking off the engagement remain unclear.**



Enten – Eller.

Et Livs-Fragment

udgivet

af

Victor Eremita.

Førſte Deel

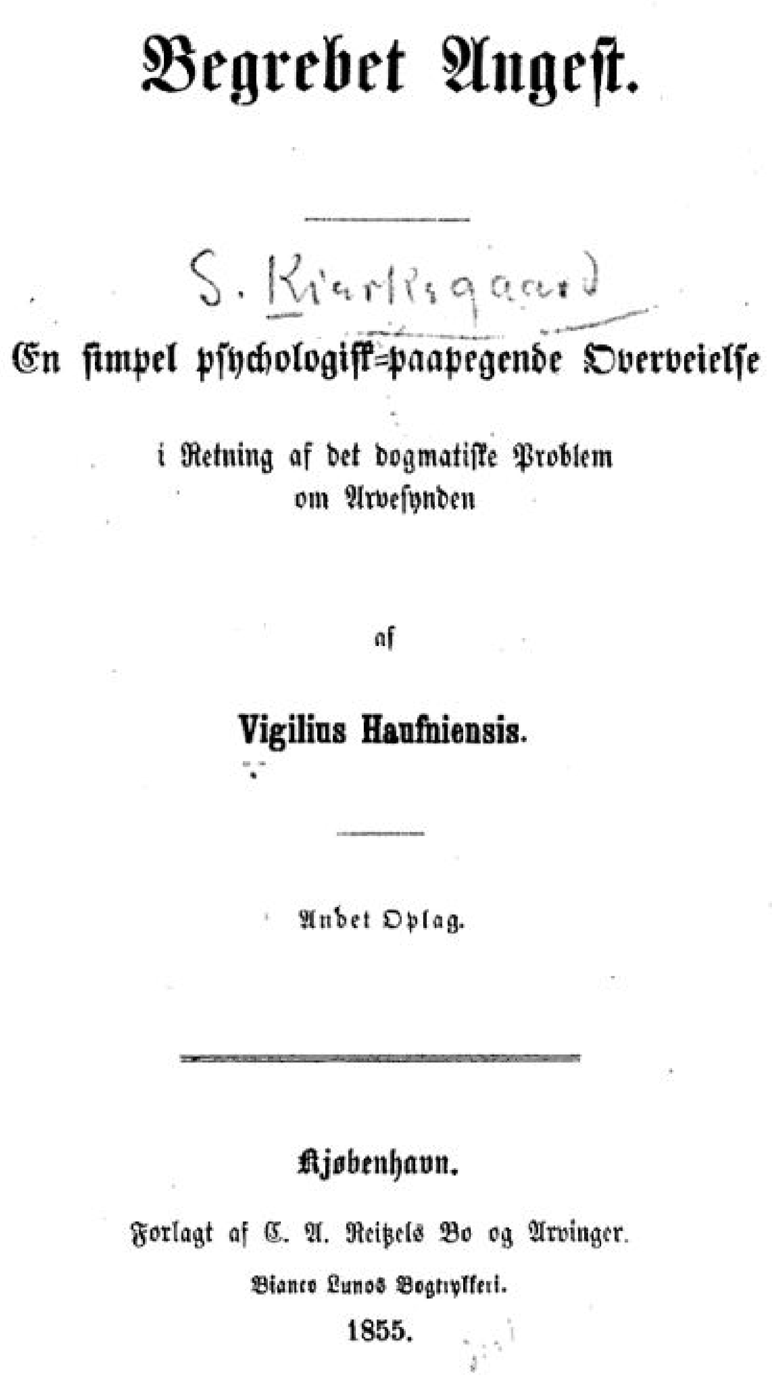
indeholdende A.'s Papirer.

Er da Fornuſten alene døbt,
ere Lidenſkaberne Hedninger?
Young.

Kjøbenhavn 1843.

Faaes hos Univerſitetsboghandler C. A. Reitzel.
Trykt i Bianco Lunos Bogtrykkeri.

Figure 4.3: **The title page of *Either - Or*, (in Danish, *Enten - Eller*).**



Begrebet Angeſt.

S. Kierkegaard

En ſimpel pſychologiſk-paapegende Overveielſe

i Retning af det dogmatiſke Problem
om Arveſynden

af

Vigilius Haufniensis.

Andet Oplag.

Kjøbenhavn.

Forlagt af C. A. Reitzels Bo og Arvinger.

Bianco Lunos Bogtrykkeri.

1855.

Figure 4.4: ***The Concept of Anxiety.***

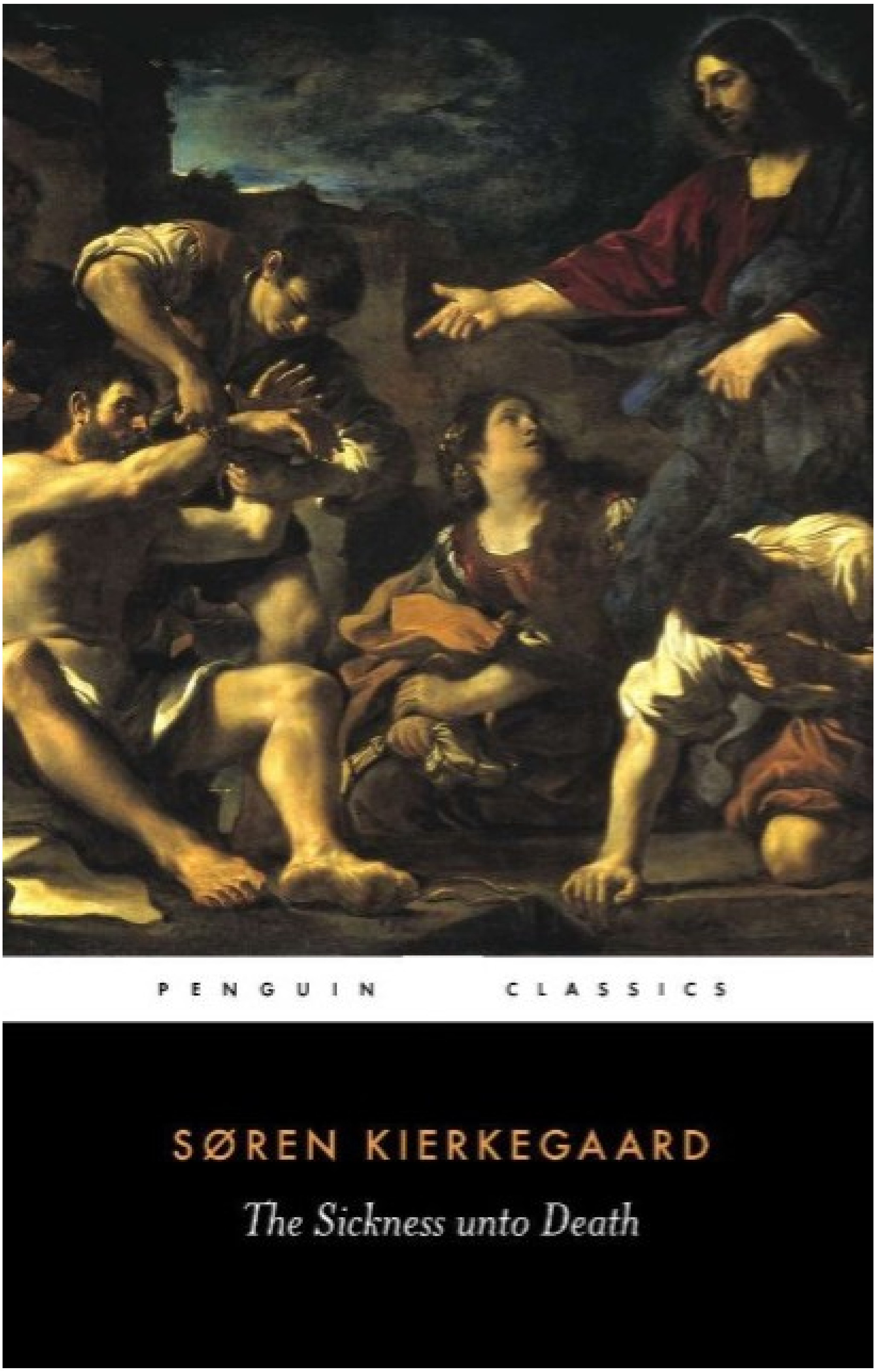


Figure 4.5: ***The Sickness Unto Death.***

Figure 4.6: **August Strindberg (1849-1912) from Sweden. Like Kierkegaard, Strindberg is considered to be an existentialist writer. August Strindberg was influenced by Kierkegaard while a student at Uppsala University (1867-1870) and mentioned him in his book *Growth of a Soul* as well as *Zones of the Spirit* (1913).**

Figure 4.7: **William James (1842-1910). He was an influential philosopher and psychologist, considered to be the "Father of American psychology". His pragmatism in philosophy was anticipated by Søren Kierkegaard. William James was the brother of the famous novelist, Henry James.**

4.2 Fyodor Dostoevsky

Wikipedia says of him:

"Dostoyevsky was a Russian novelist, philosopher, short story writer, essayist, and journalist. Dostoevsky's literary works explore human psychology in the troubled political, social, and spiritual atmospheres of 19th-century Russia, and engage with a variety of philosophical and religious themes. His most acclaimed works include *Crime and Punishment* (1866), *The Idiot* (1869), *Demons* (1872), and *The Brothers Karamazov* (1880). Dostoevsky's body of works consists of 12 novels, four novellas, 16 short stories, and numerous other works. Many literary critics rate him as one of the greatest psychological novelists in world literature. His 1864 novel *Notes from Underground* is considered to be one of the first works of existentialist literature...

"Arrested in 1849 for belonging to a literary group that discussed banned books critical of Tsarist Russia, he was sentenced to death but the sentence was commuted at the last moment. He spent four years in a Siberian prison camp, followed by six years of compulsory military service in exile. In the following years, Dostoevsky worked as a journalist, publishing and editing several magazines of his own and later A Writer's Diary, a collection of his writings. He began to travel around western Europe and developed a gambling addiction, which led to financial hardship. For a time, he had to beg for money, but he eventually became one of the most widely read and highly regarded Russian writers.

"Dostoevsky was influenced by a wide variety of philosophers and authors including Pushkin, Gogol, Augustine, Shakespeare, Dickens, Balzac, Lermontov, Hugo, Poe, Plato, Cervantes, Herzen, Kant, Belinsky, Hegel, Schiller, Solovyov, Bakunin, Sand, Hoffmann, and Mickiewicz.

"His writings were widely read both within and beyond his native Russia and influenced an equally great number of later writers including Russians such as Aleksandr Solzhenitsyn and Anton Chekhov, philosophers Friedrich Nietzsche and Jean-Paul Sartre and the emergence of Existentialism and Freudianism. His books have been translated into more than 170 languages."

Figure 4.8: **Dostoevsky, 1847.**

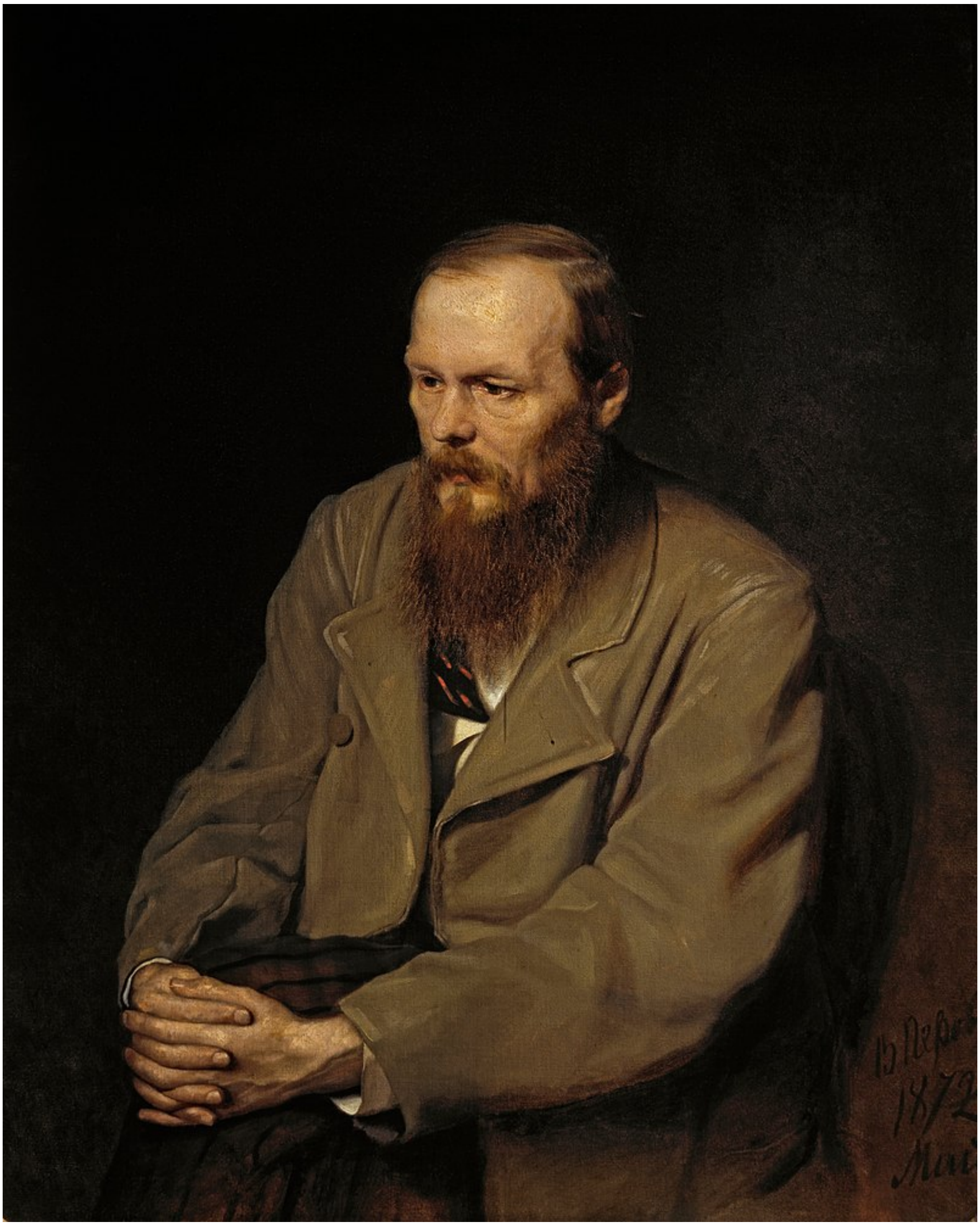


Figure 4.9: **Portrait of Dostoevsky by Vasili Perov, 1872. Dostoevsky's 1864 novel, *Notes From Underground* is considered to be one of the the first works of existentialist literature. His books have been translated into 170 languages, and they have influenced such writers and philosophers as Aleksandr Solzhenitsyn and Anton Chekhov, Friedrich Nietzsche and Jean-Paul Sartre.**

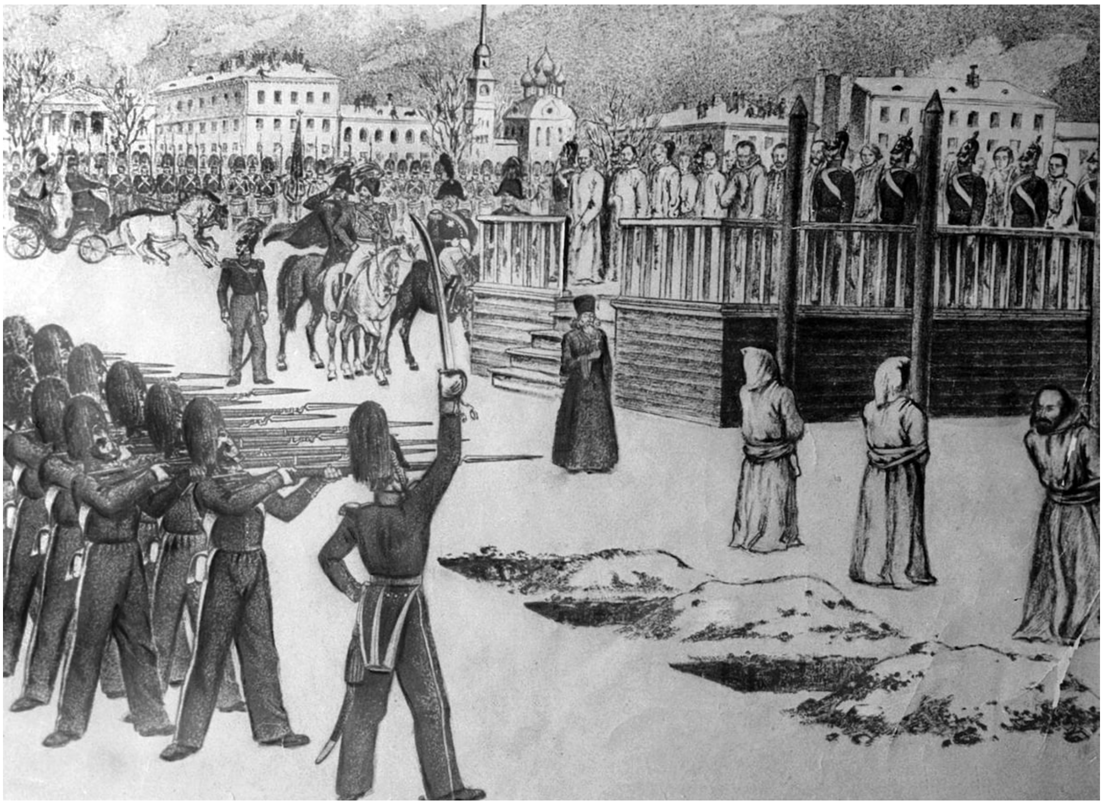


Figure 4.10: **A sketch of the Petrashevsky Circle aborted execution. The Petrashevsky Circle was a literacy group to which which Dostoevsky belonged. Its members were accused of reading and circulating books that were critical of the government, and all of the members were sentenced to death. At he last moment, a letter from the Czar arrived, commuting the sentences. Dostoevsky was sent to Siberia where, for many years, he suffered terrible hardships as a prisoner.**

4.3 Sartre: Existence is prior to essence

Here is an excerpt from Wikipedia's article on Sartre:

> **Jean-Paul Charles Aymard Sartre (1905-1980) was a French philosopher, playwright, novelist, screenwriter, political activist, biographer, and literary critic. He was one of the key figures in the philosophy of existentialism and phenomenology, and one of the leading figures in 20th-century French philosophy and Marxism. His work has also influenced sociology, critical theory, post-colonial theory, and literary studies, and continues to influence these disciplines.**
>
> **Sartre was also noted for his open relationship with prominent feminist and fellow existentialist philosopher and writer Simone de Beauvoir. Together, Sartre and de Beauvoir challenged the cultural and social assumptions and expectations of their upbringings, which they considered bourgeois, in both lifestyle and thought. The conflict between oppressive, spiritually destructive conformity (mauvaise foi, literally, 'bad faith') and an 'authentic' way of 'being' became the dominant theme of Sartre's early work, a theme embodied in his principal philosophical work Being and Nothingness (L'Etre et le Néant, 1943). Sartre's introduction to his philosophy is his work *Existentialism Is a Humanism* (*L'existentialisme est un humanisme*, 1946), originally presented as a lecture.**
>
> **He was awarded the 1964 Nobel Prize in Literature despite attempting to refuse it, saying that he always declined official honours and that 'a writer should not allow himself to be turned into an institution.'**

Figure 4.11: **Sartre in 1967. His famous maxim, “Existence is prior to essence”, conveys his belief that a person’s identity is defined more and more distinctly during his or her life by a series of events and decisions. Sartre believed that each person has a responsibility for the fate of all of humanity.**

Figure 4.12: **Simone de Beauvoir and Jean-Paul Sartre in Beijing, 1955. Although they never married, they were a couple until his death in 1980.**

Figure 4.13: **Hélène de Beauvoir's house in Goxwiller, where Sartre tried to hide from the media after being awarded the Nobel Prize.**

Figure 4.14: **Simone de Beauvoir (1908-1986) in 1967. Like Jean-Paul Sartre, she was an important existentialist writer. In addition, she was a pioneer of feminism, famous for her book, *The Second Sex.***

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Chapter 5

POSITIONAL NUMBER SYSTEMS

5.1 Positional numbers and decision trees

In the decimal system, we start by asking: How many times does the number contain $10^0 = 1$? Then we ask: How many times does the number contain $10^1 = 10$? The next step is to ask: How many times does the number contain $10^2 = 100$, and so on. Continuing in this way, we can obtain a decimal representation of any non-negative integer, no matter how large it is. We can recognize here a decision tree of the same kind that Linnaeus used to classify living organisms.

Had we been using a base-2 (binary) representation, the decision tree would have been as follows: We would first have asked: How many times does the number contain $2^0 = 1$?; then How many times does it contain $2^1 = 2$?; then How many times does it contain $2^2 = 4$?, and so on. For example the number which is written as 65 in the decimal system becomes 100001 is the binary system. It contains 1×2^6, 1×10^0, and 0 times all other powers of 2. The number written as 66 in the decimal system becomes 100010 in the binary system, while 67 becomes 100011, and 68 is represented by 100100.

5.2 Mesopotamian positional numbers

In the imagination of the Mesopotamians (the Sumerians, Elamites, Babylonians and Assyrians), the earth was a flat disc, surrounded by a rim of mountains and floating on an ocean of sweet water. Resting on these mountains was the hemispherical vault of the sky, across which moved the stars, the planets, the sun and the moon. Under the earth was another hemisphere containing the spirits of the dead. The Mesopotamians visualized the whole spherical world-universe as being immersed like a bubble in a limitless ocean of salt water.

By contrast with their somewhat primitive cosmology, both the mathematics and astronomy of the Mesopotamians were startlingly advanced. Their number system was positional, like ours, and was based on six and sixty. We can still see traces of it in our present method of measuring angles in degrees and minutes, and also in our method of measuring

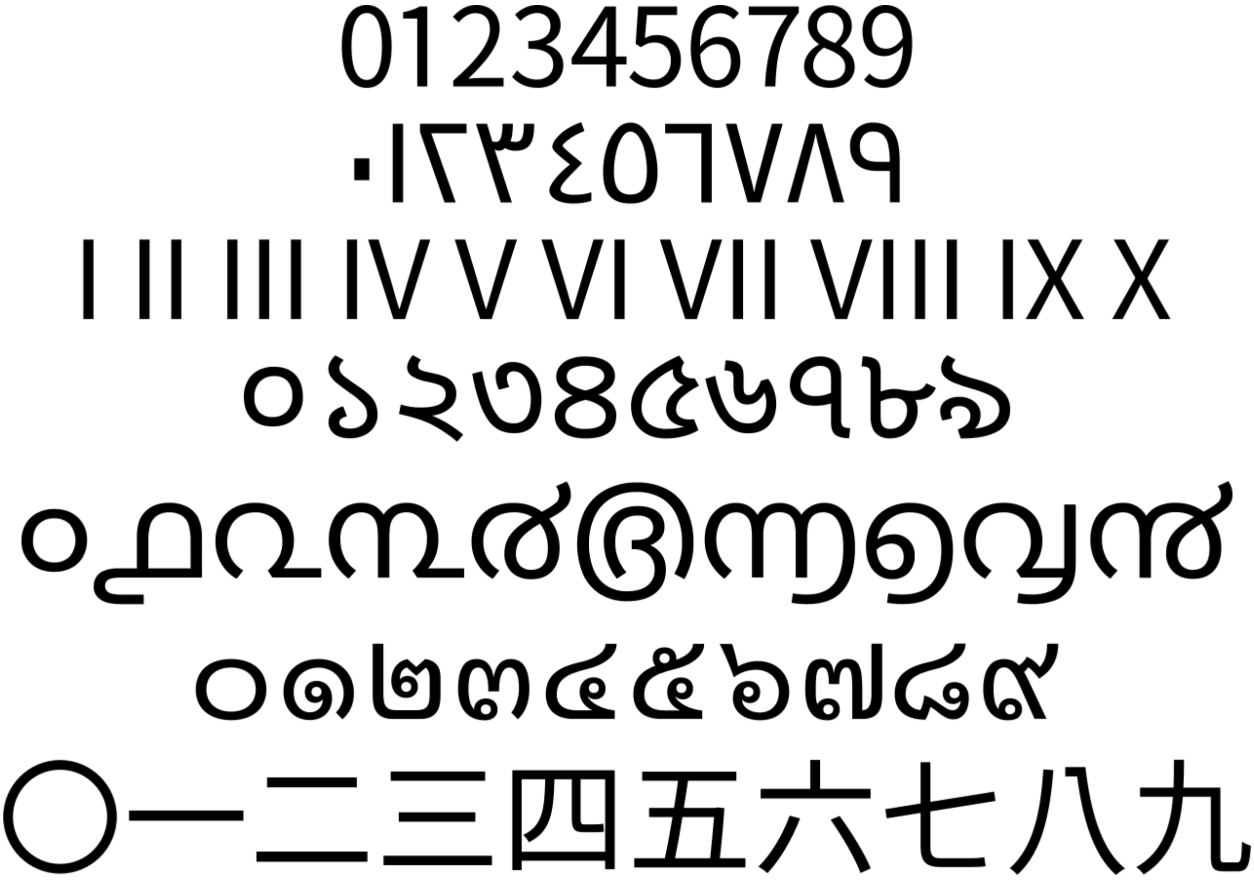


Figure 5.1: **Arabic numerals Eastern Arabic numerals Roman numerals Bengali-Assamese numerals Malayalam numerals Thai numerals Chinese numerals.**

time in hours, minutes and seconds.

The Mesopotamians were acquainted with square roots and cube roots, and they could solve quadratic equations. They also were aware of exponential and logarithmic relationships. They seemed to value mathematics for its own sake, for the sake of enjoyment and recreation, as much as for its practical applications. On the whole, their algebra was more advanced than their geometry. They knew some of the properties of triangles and circles, but did not prove them in a systematic way.

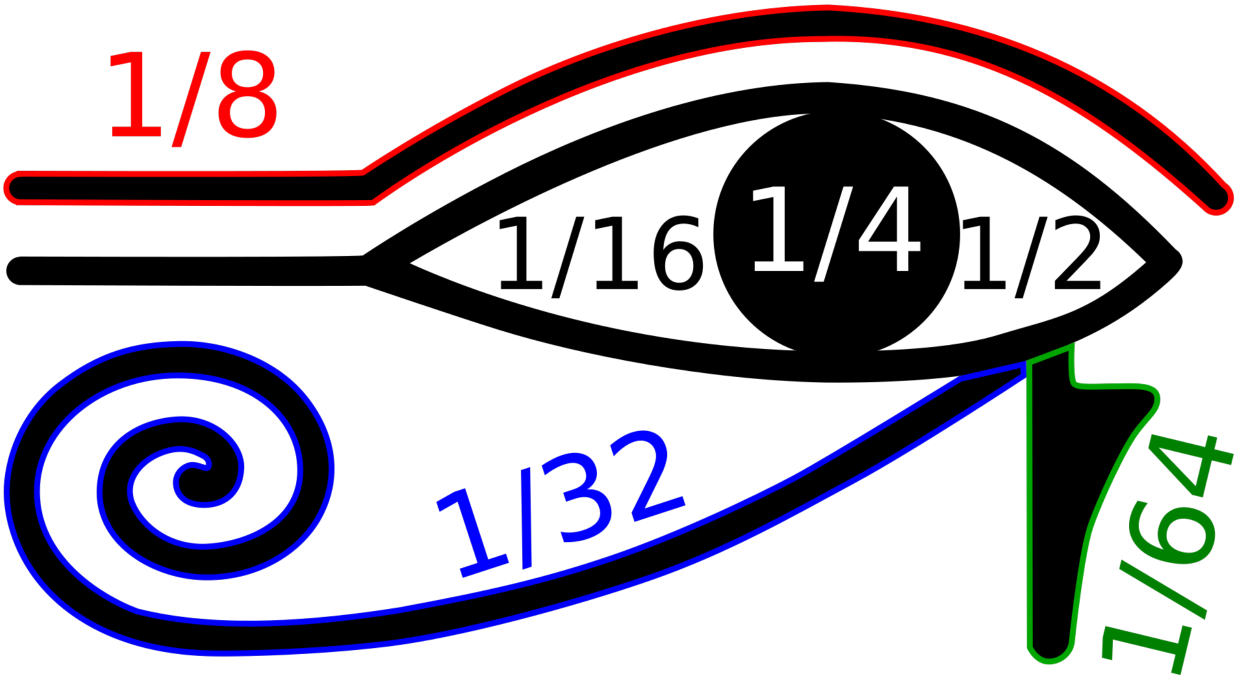


Figure 5.2: **Arithmetic values thought to have been represented by parts of the Eye of Horus.**

5.3 Indian and Arabic positional numbers

In ancient Indian mathematics, algebra and trigonometry were especially highly developed. For example, the astronomer Brahmagupta (598 A.D. - 660 A.D.) applied algebraic methods to astronomical problems. The notation for zero and the decimal system were invented in India, probably during the 8th or 9th century A.D.. These mathematical techniques were later transmitted to Europe by the Arabs.

5.4 Boolean algebra

Discussing George Boole's famous book, *The Laws of Thought*, Wikipedia says:

> **"The historian of logic John Corcoran wrote an accessible introduction to Laws of Thought[1] and a point by point comparison of Prior Analytics and Laws of Thought. According to Corcoran, Boole fully accepted and endorsed Aristotle's logic. Boole's goals were 'to go under, over, and beyond' Aristotle's logic by:**
>
> 1. **Providing it with mathematical foundations involving equations;**

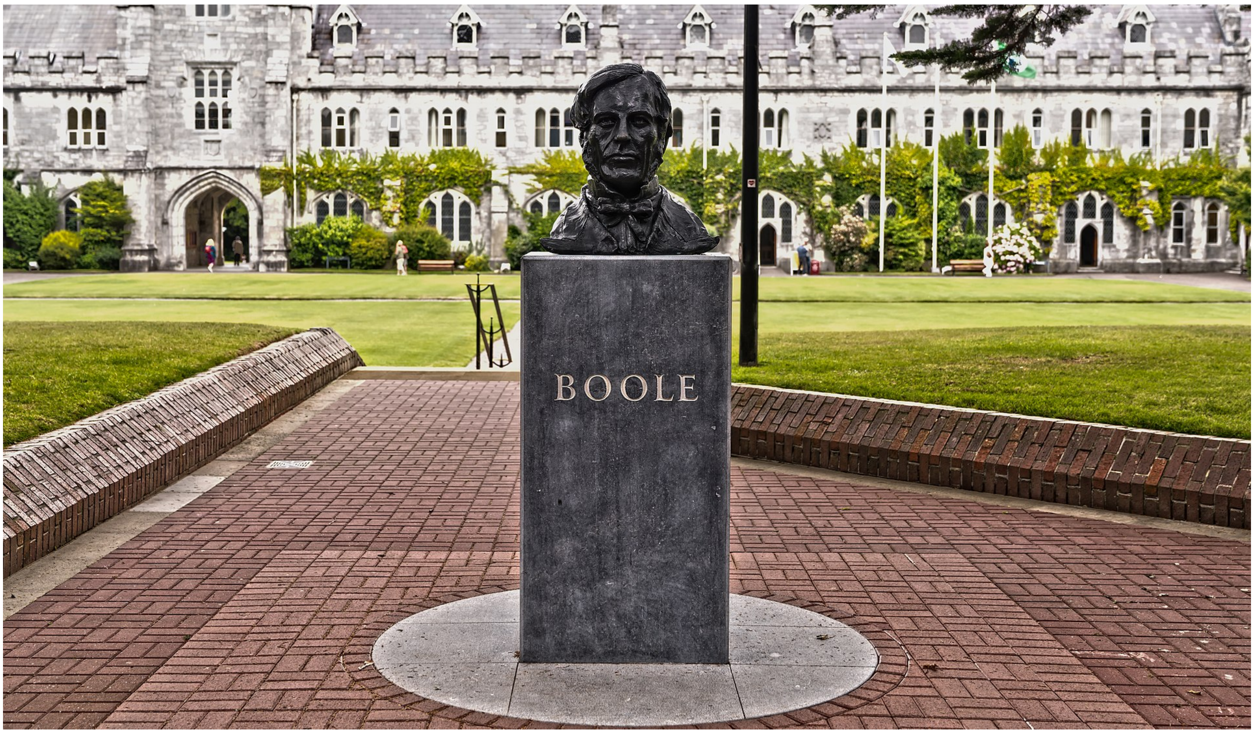
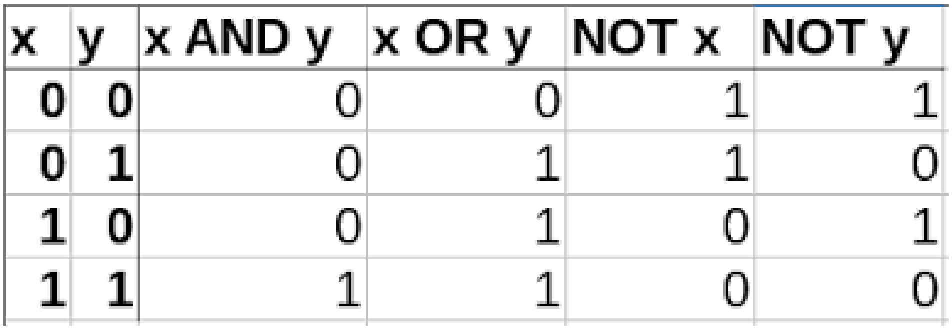
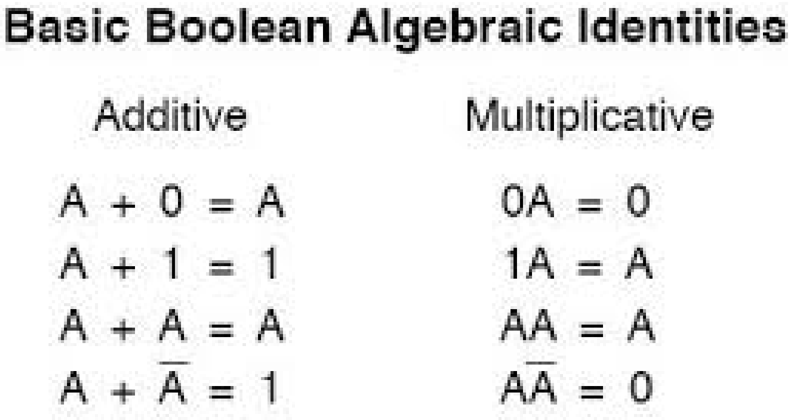


Figure 5.3: **Bust of George Boole (1815-1864) at University College Cork. Largely self-taught as a mathematician, Boole served as the first professor of mathematics at Queen's College, Cork, Ireland. He is remembered today for his book, *The Laws of Thought*, which gave Aristotelean logic a mathematical form, extended its range of application, and laid an important foundation of the information age. Modern computers make use of circuits incorporating Boolean logic and decision trees.**



x	y	x AND y	x OR y	NOT x	NOT y
0	0	0	0	1	1
0	1	0	1	1	0
1	0	0	1	0	1
1	1	1	1	0	0



Basic Boolean Algebraic Identities

Additive	Multiplicative
$A + 0 = A$	$0A = 0$
$A + 1 = 1$	$1A = A$
$A + A = A$	$AA = A$
$A + \overline{A} = 1$	$A\overline{A} = 0$

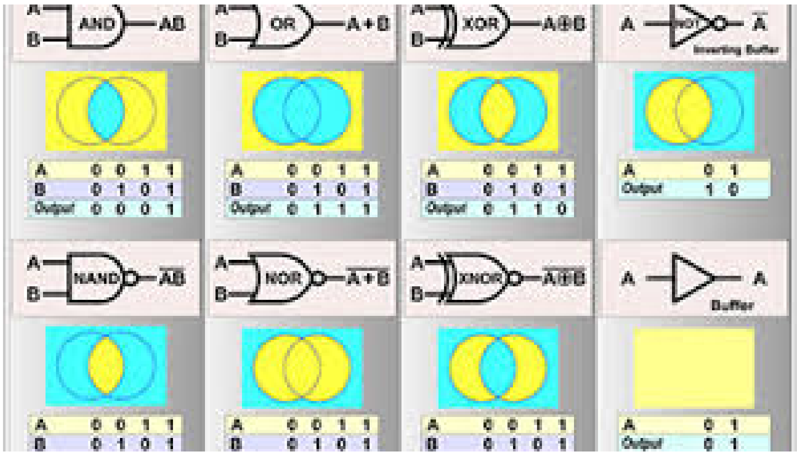


Figure 5.4: **Boolean logic circuits are used in modern computers.**

2. **Extending the class of problems it could treat from assessing validity to solving equations, and;**
3. **Expanding the range of applications it could handle - e.g. from propositions having only two terms to those having arbitrarily many.**

"More specifically, Boole agreed with what Aristotle said; Boole's 'disagreements', if they might be called that, concern what Aristotle did not say. First, in the realm of foundations, Boole reduced the four propositional forms of Aristotle's logic to formulas in the form of equations - by itself a revolutionary idea. Second, in the realm of logic's problems, Boole's addition of equation solving to logic - another revolutionary idea - involved Boole's doctrine that Aristotle's rules of inference (the 'perfect syllogisms') must be supplemented by rules for equation solving. Third, in the realm of applications, Boole's system could handle multi-term propositions and arguments whereas Aristotle could handle only two-termed subject-predicate propositions and arguments. For example, Aristotle's system could not deduce 'No quadrangle that is a square is a rectangle that is a rhombus' from 'No square that is a quadrangle is a rhombus that is a rectangle' or from 'No rhombus that is a rectangle is a square that is a quadrangle'."

5.5 Shannon and information theory

Claude Shannon is usually considered to be the "father of information theory". Shannon graduated from the University of Michigan in 1936, and he later obtained a Ph.D. in mathematics from the Massachusetts Institute of Technology. He worked at the Bell Telephone Laboratories, and later became a professor at MIT. In 1949, motivated by the need of AT&T to quantify the amount of information that could be transmitted over a given line, Shannon published a pioneering study of information as applied to communication and computers. Shannon first examined the question of how many binary digits are needed to express a given integer Ω. In the decimal system we express an integer by telling how many 1's it contains, how many 10's, how many 100's, how many 1000's, and so on. Thus, for example, in the decimal system,

$$105 = 1 \times 10^2 + 0 \times 10^1 + 1 \times 10^0 \tag{5.1}$$

Any integer greater than or equal to 100 but less than 1000 can be expressed with 3 decimal digits; any number greater than or equal to 1000 but less than 10,000 requires 4, and so on.

The natural language of computers is the binary system; and therefore Shannon asked himself how many binary digits are needed to express an integer of a given size. In the binary system, a number is specified by telling how many of the various powers of 2 it contains. Thus, the decimal integer 105, expressed in the binary system, is

$$1101001 \equiv 1 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 \tag{5.2}$$

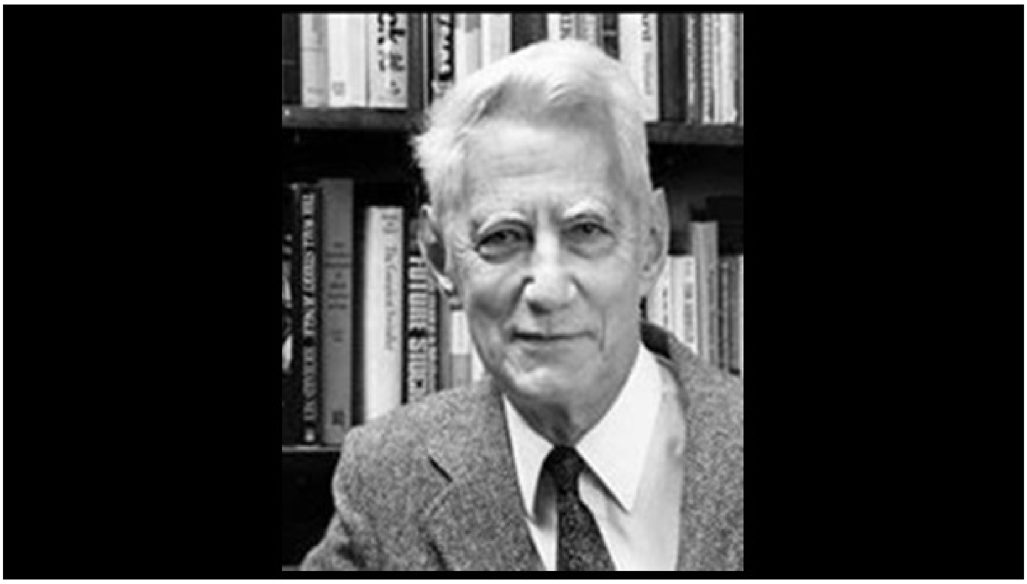


Figure 5.5: **Claude Shannon.**

In the many early computers, numbers and commands were read in on punched paper tape, which could either have a hole in a given position, or else no hole. Shannon wished to know how long a strip of punched tape is needed to express a number of a given size - how many binary digits are needed? If the number happens to be an exact power of 2, then the answer is easy: To express the integer

$$\Omega = 2^n \tag{5.3}$$

one needs $n + 1$ binary digits. The first binary digit, which is 1, gives the highest power of 2, and the subsequent digits, all of them 0, specify that the lower powers of 2 are absent. Shannon introduced the word "bit" as an abbreviation of "binary digit". He generalized this result to integers which are not equal to exact powers of 2: Any integer greater than or equal to 2^{n-l}, but less than 2^n, requires n binary digits or "bits". In Shannon's theory, the bit became the unit of information. He defined the quantity of information needed to express an arbitrary integer Ω as

$$I = \log_2 \Omega \text{bits} = \frac{\ln \Omega}{\ln 2} \text{ bits} = 1.442695 \ \ln \Omega \text{ bits} \tag{5.4}$$

or

$$I = K \ln \Omega \qquad\qquad K = 1.442695 \text{ bits} \tag{5.5}$$

Of course the information function I, as defined by equation (4.13), is in general not an integer, but if one wishes to find the exact number of binary digits required to express a given integer Ω, one can calculate I and round upwards[1].

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[1] Similar considerations can also be found in the work of the statistician R.A. Fisher.

Shannon went on to consider quantitatively the amount of information which is missing before we perform an experiment, the result of which we are unable to predict with certainty. (For example, the "experiment" might be flipping a coin or throwing a pair of dice.) Shannon first calculated the missing information, I_N, not for a single performance of the experiment but for N independent performances. Suppose that in a single performance, the probability that a particular result i will occur is given by P_i. If the experiment is performed N times, then as N becomes very large, the fraction of times that the result i occurs becomes more and more exactly equal to P_i. For example, if a coin is flipped N times, then as N becomes extremely large, the fraction of "heads" among the results becomes more and more nearly equal to 1/2. However, some information is still missing because we still do not know the sequence of the results. Shannon was able to show from combinatorial analysis, that this missing information about the sequence of the results is given by

$$I_N = K \ln \Omega \tag{5.6}$$

where

$$\Omega = \frac{N!}{n_1! n_2! n_3! ... n_i! ...} \qquad\qquad n_i \equiv N P_i \tag{5.7}$$

or

$$I_N = K \ln \Omega = K \left[\ln(N!) - \sum_i \ln(n_i) \right] \tag{5.8}$$

Shannon then used Sterling's approximation, $\ln(n_i!) \approx n_i(\ln n_i - 1)$, to rewrite (4.16) in the form

$$I_N = -KN \sum_i P_i \ln P_i \tag{5.9}$$

Finally, dividing by N, he obtained the missing information prior to the performance of a single experiment:

$$I = -K \sum_i P_i \ln P_i \tag{5.10}$$

For example, in the case of flipping a coin, Shannon's equation tells us that the missing information is

$$I = -K \left[\frac{1}{2} \ln \left(\frac{1}{2} \right) + \frac{1}{2} \ln \left(\frac{1}{2} \right) \right] = 1 \text{ bit} \tag{5.11}$$

As a second example, we might think of an "experiment" where we write all 26 letters of the English alphabet on 26 small pieces of paper. We then place them in a hat and draw out one at random. In this second example,

$$P_a = P_b = ... = P_z = \frac{1}{26} \tag{5.12}$$

and from Shannon's equation we can calculate that before the experiment is performed, the missing information is

$$I = -K \left[\frac{1}{26} \ln \left(\frac{1}{26} \right) + \frac{1}{26} \ln \left(\frac{1}{26} \right) + ... \right] = 4.70 \text{ bits} \tag{5.13}$$

If we had instead picked a letter at random out of an English book, the letters would not occur with equal probability. From a statistical analysis of the frequency of the letters, we would know in advance that

$$P_a = 0.078, \qquad P_b = 0.013, \qquad ... \qquad P_z = 0.001 \tag{5.14}$$

Shannon's equation would then give us a slightly reduced value for the missing information:

$$I = -K\left[0.078 \ln 0.078 + 0.013 \ln 0.013 + ...\right] = 4.15 \text{ bits} \tag{5.15}$$

Less information is missing when we know the frequencies of the letters, and Shannon's formula tells us exactly how much less information is missing.

When Shannon had been working on his equations for some time, he happened to visit the mathematician John von Neumann, who asked him how he was getting on with his theory of missing information. Shannon replied that the theory was in excellent shape, except that he needed a good name for "missing information". "Why don't you call it entropy?", von Neumann suggested. "In the first place, a mathematical development very much like yours already exists in Boltzmann's statistical mechanics, and in the second place, no one understands entropy very well, so in any discussion you will be in a position of advantage!" Shannon took von Neumann's advice, and used the word "entropy" in his pioneering paper on information theory. Missing information in general cases has come to be known as "Shannon entropy". But Shannon's ideas can also be applied to thermodynamics.

Entropy expressed as missing information

From the standpoint of information theory, the thermodynamic entropy S_N of an ensemble of N identical weakly-interacting systems in a given macrostate can be interpreted as the missing information which we would need in order to specify the state of each system, i.e. the microstate of the ensemble. Thus, thermodynamic information is defined to be the negative of thermodynamic entropy, i.e. the information that would be needed to specify the microstate of an ensemble in a given macrostate. Shannon's formula allows this missing information to be measured quantitatively. Applying Shannon's formula, equation (4.13), to the missing information in Boltzmann's problem we can identify W with Ω, S_N with I_N, and k with K:

$$W \to \Omega \qquad S_N \to I_N \qquad k \to K = \frac{1}{\ln 2} \text{ bits} \tag{5.16}$$

so that

$$k \ln 2 = 1 \text{ bit} = 0.95697 \times 10^{-23} \, \frac{\text{joule}}{\text{kelvin}} \tag{5.17}$$

and

$$k = 1.442695 \text{ bits} \tag{5.18}$$

This implies that temperature has the dimension energy/bit:

$$1 \text{ degree Kelvin} = 0.95697 \times 10^{-23} \, \frac{\text{joule}}{\text{bit}} \tag{5.19}$$

From this it follows that

$$1 \, \frac{\text{joule}}{\text{kelvin}} = 1.04496 \times 10^{23} \text{ bits} \tag{5.20}$$

If we divide equation (4.28) by Avogadro's number we have

$$1 \, \frac{\text{joule}}{\text{kelvin mol}} = \frac{1.04496 \times 10^{23} \text{ bits/molecule}}{6.02217 \times 10^{23} \text{ molecules/mol}} = 0.17352 \, \frac{\text{bits}}{\text{molecule}} \tag{5.21}$$

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Chapter 6

THE HISTORY OF COMPUTERS

6.1 Pascal and Leibniz

If civilization survives, historians in the distant future will undoubtedly regard the invention of computers as one of the most important steps in human cultural evolution - as important as the invention of writing or the invention of printing. The possibilities of artificial intelligence have barely begun to be explored, but already the impact of computers on society is enormous.

The first programmable universal computers were completed in the mid-1940's; but they had their roots in the much earlier ideas of Blaise Pascal (1623-1662), Gottfried Wilhelm Leibniz (1646-1716), Joseph Marie Jacquard (1752-1834) and Charles Babbage (1791-1871).

In 1642, the distinguished French mathematician and philosopher Blaise Pascal completed a working model of a machine for adding and subtracting. According to tradition, the idea for his "calculating box" came to Pascal when, as a young man of 17, he sat thinking of ways to help his father (who was a tax collector). In describing his machine, Pascal wrote: "I submit to the public a small machine of my own invention, by means of which you alone may, without any effort, perform all the operations of arithmetic, and may be relieved of the work which has often times fatigued your spirit when you have worked with the counters or with the pen."

Pascal's machine worked by means of toothed wheels. It was much improved by Leibniz, who constructed a mechanical calculator which, besides adding and subtracting, could also multiply and divide. His first machine was completed in 1671; and Leibniz' description of it, written in Latin, is preserved in the Royal Library at Hanover: "There are two parts of the machine, one designed for addition (and subtraction), and the other designed for multiplication (and division); and they should fit together. The adding (and subtracting) machine coincides completely with the calculating box of Pascal. Something, however, must be added for the sake of multiplication..."

"The wheels which represent the multiplicand are all of the same size, equal to that of the wheels of addition, and are also provided with ten teeth which, however, are movable

Figure 6.1: **Blaise Pascal (1623-1662) was a French mathematician, physicist, writer, inventor and theologian. Pascal, a child prodigy, was educated by his father, who was a tax-collector. He invented his calculating box to make his father's work less tedious.**

Figure 6.2: **The German mathematician, philosopher and universal genius Gottfried Wilhelm von Leibniz (1646-1716) was a contemporary of Isaac Newton. He invented differential and integral calculus independently, just as Newton had done many years earlier. However, Newton had not published his work on calculus, and thus a bitter controversy over priority was precipitated. When his patron, the Elector of Hanover moved to England to become George I, Leibniz was left behind because the Elector feared that the controversy would alienate the English. Leibniz extended Pascal's calculating box so that it could perform multiplication and division. Calculators of his design were still being used in the 1960's.**

so that at one time there should protrude 5, at another 6 teeth, etc., according to whether the multiplicand is to be represented five times or six times, etc."

"For example, the multiplicand 365 consists of three digits, 3, 6, and 5. Hence the same number of wheels is to be used. On these wheels, the multiplicand will be set if from the right wheel there protrude 5 teeth, from the middle wheel 6, and from the left wheel 3."

6.2 Jacquard and Babbage

By 1810, calculating machines based on Leibniz' design were being manufactured commercially; and mechanical calculators of a similar (if much improved) design could be found in laboratories and offices until the 1960's. The idea of a programmable universal computer is due to the English mathematician, Charles Babbage, who was the Lucasian Professor of Mathematics at Cambridge University. (In the 17th century, Isaac Newton held this post, and in the 20th century, P.A.M. Dirac and Stephen Hawking also held it.)

In 1812, Babbage conceived the idea of constructing a machine which could automat-

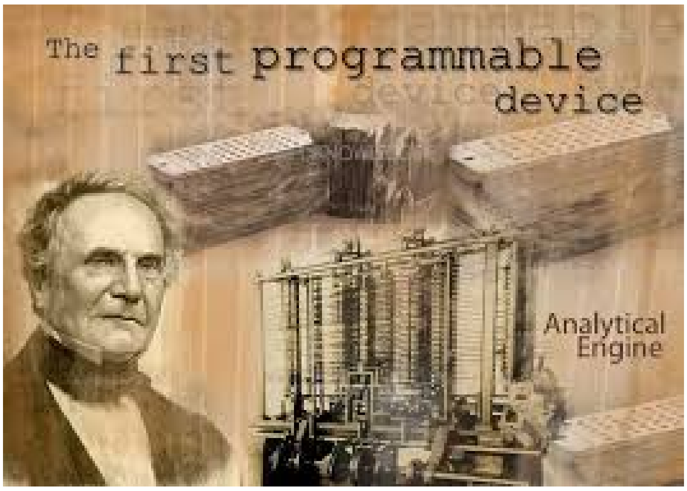

Figure 6.3: **Charles Babbage (1791-1871) and his analytical engine.**

ically produce tables of functions, provided that the functions could be approximated by polynomials. He constructed a small machine, which was able to calculate tables of quadratic functions to eight decimal places, and in 1832 he demonstrated this machine to the Royal Society and to representatives of the British government.

The demonstration was so successful that Babbage secured financial support for the construction of a large machine which would tabulate sixth-order polynomials to twenty decimal places. The large machine was never completed, and twenty years later, after having spent seventeen thousand pounds on the project, the British government withdrew its support. The reason why Babbage's large machine was never finished can be understood from the following account by Lord Moulton of a visit to the mathematician's laboratory:

"One of the sad memories of my life is a visit to the celebrated mathematician and inventor, Mr. Babbage. He was far advanced in age, but his mind was still as vigorous as ever. He took me through his workrooms."

"In the first room I saw the parts of the original Calculating Machine, which had been shown in an incomplete state many years before, and had even been put to some use. I asked him about its present form. 'I have not finished it, because in working at it, I came on the idea of my Analytical Machine, which would do all that it was capable of doing, and much more. Indeed, the idea was so much simpler that it would have taken more work to complete the Calculating Machine than to design and construct the other in its entirety; so I turned my attention to the Analytical Machine.'"

"After a few minutes talk, we went into the next workroom, where he showed me the working of the elements of the Analytical Machine. I asked if I could see it. 'I have never completed it,' he said, 'because I hit upon the idea of doing the same thing by a different and far more effective method, and this rendered it useless to proceed on the old lines.'"

"Then we went into a third room. There lay scattered bits of mechanism, but I saw no trace of any working machine. Very cautiously I approached the subject, and received the dreaded answer: 'It is not constructed yet, but I am working at it, and will take less time

Figure 6.4: **Joseph Marie Jacquard (1752-1834) invented a loom which could be programed to produce any design by means of punched cards. News of his invention inspired Babbage to invent a universal programmable computing machine.**

to construct it altogether than it would have taken to complete the Analytical Machine from the stage in which I left it.' I took leave of the old man with a heavy heart."

Babbage's first calculating machine was a special-purpose mechanical computer, designed to tabulate polynomial functions; and he abandoned this design because he had hit on the idea of a universal programmable computer. Several years earlier, the French inventor Joseph Marie Jacquard had constructed an automatic loom in which large wooden "punched cards" were used to control the warp threads. Inspired by Jacquard's invention, Babbage planned to use punched cards to program his universal computer. (Jacquard's looms could be programmed to weave extremely complex patterns: A portrait of the inventor, woven on one of his looms in Lyon, hung in Babbage's drawing room.)

One of Babbage's frequent visitors was Augusta Ada[1], Countess of Lovelace (1815-1852), the daughter of Lord and Lady Byron. She was a mathematician of considerable ability, and it is through her lucid descriptions that we know how Babbage's never-completed Analytical Machine was to have worked.

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[1] The programming language ADA is named after her.

Figure 6.5: **Jacquard's loom.**

Figure 6.6: **Lord Byron's daughter, Augusta Ada, Countess of Lovelace (1815-1852) was an accomplished mathematician and a frequent visitor to Babbage's workshop. It is through her lucid description of his ideas that we know how Babbage's universal calculating machine was to have worked. The programming language ADA is named after her.**

6.3 Harvard's sequence-controlled calculator

The next step towards modern computers was taken by Herman Hollerith, a statistician working for the United States Bureau of the Census. He invented electromechanical machines for reading and sorting data punched onto cards. Hollerith's machines were used to analyze the data from the 1890 United States Census. Because the Census Bureau was a very limited market, Hollerith branched out and began to manufacture similar machines for use in business and administration. His company was later bought out by Thomas J. Watson, who changed its name to International Business Machines.

In 1937, Howard Aiken, of Harvard University, became interested in combining Babbage's ideas with some of the techniques which had developed from Hollerith's punched card machines. He approached the International Business Machine Corporation, the largest manufacturer of punched card equipment, with a proposal for the construction of a large, automatic, programmable calculating machine.

Aiken's machine, the Automatic Sequence Controlled Calculator (ASCC), was completed in 1944 and presented to Harvard University. Based on geared wheels, in the Pascal-Leibniz-Babbage tradition, ASCC had more than three quarters of a million parts and used 500 miles of wire. ASCC was unbelievably slow by modern standards - it took three-tenths of a second to perform an addition - but it was one of the first programmable general-purpose digital computers ever completed. It remained in continuous use, day and night, for fifteen years.

Figure 6.7: **The Automatic Sequence-Controlled Calculator ASCC can still be seen by visitors at Harvard's science building and cafeteria.**

6.4 The first electronic computers

In the ASCC, binary numbers were represented by relays, which could be either on or off. The on position represented 1, while the off position represented 0, these being the only two digits required to represent numbers in the binary (base 2) system. Electromechanical calculators similar to ASCC were developed independently by Konrad Zuse in Germany and by George R. Stibitz at the Bell Telephone Laboratory.

Electronic digital computers

In 1937, the English mathematician A.M. Turing published an important article in the Proceedings of the London Mathematical Society in which envisioned a type of calculating machine consisting of a long row of cells (the "tape"), a reading and writing head, and a set of instructions specifying the way in which the head should move the tape and modify the state and "color" of the cells on the tape. According to a hypothesis which came to be known as the "Church-Turing hypothesis", the type of computer proposed by Turing was capable of performing every possible type of calculation. In other words, the Turing machine could function as a universal computer.

In 1943, a group of English engineers, inspired by the ideas of Alan Turing and those of the mathematician M.H.A. Newman, completed the electronic digital computer Colossus. Colossus was the first large-scale electronic computer. It was used to break the German Enigma code; and it thus affected the course of World War II.

In 1946, ENIAC (Electronic Numerical Integrator and Calculator) became operational. This general-purpose computer, designed by J.P. Eckert and J.W. Mauchley of the University of Pennsylvania, contained 18,000 vacuum tubes, one or another of which was often out of order. However, during the periods when all its vacuum tubes were working, an electronic computer like Colossus or ENIAC could shoot ahead of an electromechanical machine (such as ASCC) like a hare outdistancing a tortoise.

During the summer of 1946, a course on "The Theory and Techniques of Electronic Digital Computers" was given at the University of Pennsylvania. The ideas put forward in this course had been worked out by a group of mathematicians and engineers headed by J.P. Eckert, J.W. Mauchley and John von Neumann, and these ideas very much influenced all subsequent computer design.

Cybernetics

The word "Cybernetics", was coined by the American mathematician Norbert Wiener (1894-1964) and his colleagues, who defined it as "the entire field of control and communication theory, whether in the machine or in the animal". Wiener derived the word from the Greek term for "steersman".

Norbert Wiener began life as a child prodigy: He entered Tufts University at the age of 11 and received his Ph.D. from Harvard at 19. He later became a professor of mathematics at the Massachusetts Institute of Technology. In 1940, with war on the horizon,

Figure 6.8: **Alan Turing (1912-1954). He is considered to be the father of theoretical computer science. During World War II, Turing's work allowed the allies to crack the German's code. This appreciably shortened the length of the war in Europe, and saved many lives.**

Figure 6.9: **John von Neumann (1903-1957, right) with J. Robert Oppenheimer. In the background is an electronic digital computer.**

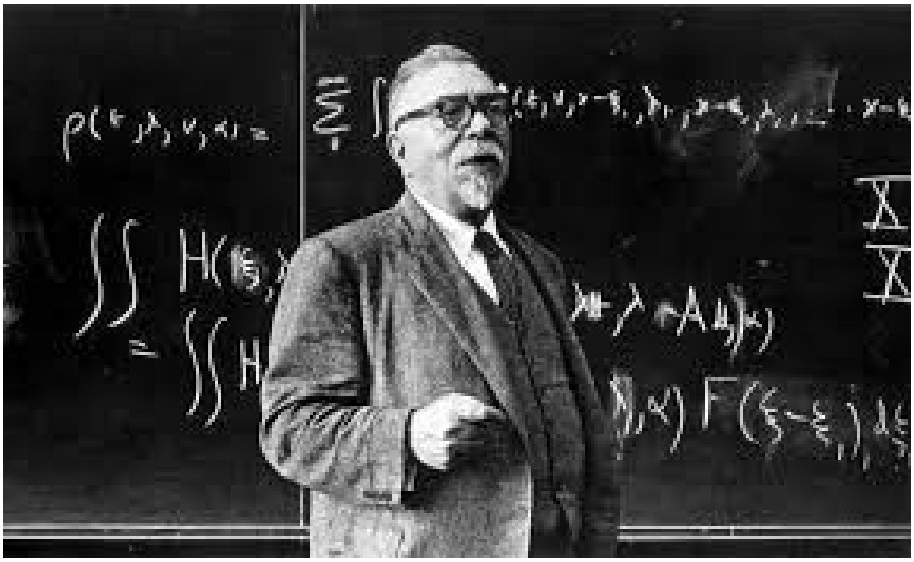

Figure 6.10: **MIT's Norbert Wiener (1894-1964) coined the word "Cybernetics", derived from a Greek word meaning "steersman". Wiener was one of the principle organizers of the Macy Conferences.**

Wiener sent a memorandum to Vannevar Bush, another MIT professor who had done pioneering work with analogue computers, and had afterwards become the chairman of the U.S. National Defense Research Committee. Wiener's memorandum urged the American government to support the design and construction of electronic digital computers, which would make use of binary numbers, vacuum tubes, and rapid memories. In such machines, the memorandum emphasized, no human intervention should be required except when data was to be read into or out of the machine.

Like Leo Szilard, John von Neumann, Claude Shannon and Erwin Schrödinger, Norbert Wiener was aware of the relation between information and entropy. In his 1948 book Cybernetics he wrote: "...we had to develop a statistical theory of the amount of information, in which the unit amount of information was that transmitted by a single decision between equally probable alternatives. This idea occurred at about the same time to several writers, among them the statistician R.A. Fisher, Dr. Shannon of Bell Telephone Laboratories, and the author. Fisher's motive in studying this subject is to be found in classical statistical theory; that of Shannon in the problem of coding information; and that of the author in the problem of noise and message in electrical filters... The notion of the amount of information attaches itself very naturally to a classical notion in statistical mechanics: that of entropy. Just as the amount of information in a system is a measure of its degree of organization, so the entropy of a system is a measure of its degree of disorganization; and the one is simply the negative of the other."

During World War II, Norbert Wiener developed automatic systems for control of anti-aircraft guns. His systems made use of feedback loops closely analogous to those with which animals coordinate their movements. In the early 1940's, he was invited to attend a

Figure 6.11: **Margaret Mead (1901-1978) and Gregory Bateson (1904-1980). They used the feedback loops studied by Wiener to explain many aspects of human behavior. Bateson is considered to be one of the main founders of the discipline Biosemiotics, which considers information to be the central feature of living organisms.**

series of monthly dinner parties organized by Arturo Rosenbluth, a professor of physiology at Harvard University. The purpose of these dinners was to promote discussions and collaborations between scientists belonging to different disciplines. The discussions which took place at these dinners made both Wiener and Rosenbluth aware of the relatedness of a set of problems that included homeostasis and feedback in biology, communication and control mechanisms in neurophysiology, social communication among animals (or humans), and control and communication involving machines.

Wiener and Rosenbluth therefore tried to bring together workers in the relevant fields to try to develop common terminology and methods. Among the many people whom they contacted were the anthropologists Gregory Bateson and Margaret Mead, Howard Aiken (the designer of the Automatic Sequence Controlled Calculator), and the mathematician John von Neumann. The Josiah Macy Jr. Foundation sponsored a series of ten yearly meetings, which continued until 1949 and which established cybernetics as a new research discipline. It united areas of mathematics, engineering, biology, and sociology which had previously been considered unrelated. Among the most important participants (in addition to Wiener, Rosenbluth, Bateson, Mead, and von Neumann) were Heinz von Foerster, Kurt Lewin, Warren McCulloch and Walter Pitts. The Macy conferences were small and informal, with an emphasis on discussion as opposed to the presentation of formal papers. A stenographic record of the last five conferences has been published, edited by von Foerster. Transcripts of the discussions give a vivid picture of the enthusiastic and creative atmosphere of the meetings. The participants at the Macy Conferences perceived Cybernetics as a much-needed bridge between the natural sciences and the humanities. Hence their enthusiasm. Wiener's feedback loops and von Neumann's theory of games were used by anthropologists Mead and Bateson to explain many aspects of human behavior.

6.5 Biosemiotics

The Oxford Dictionary of Biochemistry and Molecular Biology (Oxford University Press, 1997) defines Biosemiotics as "the study of signs, of communication, and of information in living organisms". The biologists Claus Emmeche and K. Kull offer another definition of Biosemiotics: "biology that interprets living systems as sign systems".

The American philosopher Charles Sanders Peirce (1839-1914) is considered to be one of the founders of Semiotics (and hence also of Biosemiotics). Peirce studied philosophy and chemistry at Harvard, where his father was a professor of mathematics and astronomy. He wrote extensively on philosophical subjects, and developed a theory of signs and meaning which anticipated many of the principles of modern Semiotics. Peirce built his theory on a triad: (1) the sign, which represents (2) something to (3) somebody. For example, the sign might be a broken stick, which represents a trail to a hunter, it might be the arched back of a cat, which represents an aggressive attitude to another cat, it might be the waggle-dance of a honey bee, which represents the coordinates of a source of food to her hive-mates, or it might be a molecule of trans-10-cis-hexadecadienol, which represents irresistible sexual temptation to a male moth of the species Bombyx mori. The sign might be a sequence of nucleotide bases which represents an amino acid to the ribosome-transfer-RNA system, or it might be a cell-surface antigen which represents self or non-self to the immune system. In information technology, the sign might be the presence or absence of a pulse of voltage, which represents a binary digit to a computer. Semiotics draws our attention to the sign and to its function, and places much less emphasis on the physical object which forms the sign. This characteristic of the semiotic viewpoint has been expressed by the Danish biologist Jesper Hoffmeyer in the following words: "The sign, rather than the molecule, is the basic unit for studying life."

A second important founder of Biosemiotics was Jakob von Uexküll (1864-1944). He was born in Estonia, and studied zoology at the University of Tartu. After graduation, he worked at the Institute of Physiology at the University of Heidelberg, and later at the Zoological Station in Naples. In 1907, he was given an honorary doctorate by Heidelberg

Figure 6.12: **Charles Sanders Pearce (1839-1914).**

Figure 6.13: **Jakob Johann Baron von Uexküll (1964-1944). Together with Pearce and Bateson, he is one of the principle founders of Biosemiotics.**

for his studies of the physiology of muscles. Among his discoveries in this field was the first recognized instance of negative feedback in an organism. Von Uexküll's later work was concerned with the way in which animals experience the world around them. To describe the animal's subjective perception of its environment he introduced the word Umwelt; and in 1926 he founded the Institut fur Umweltforschung at the University of Heidelberg. Von Uexküll visualized an animal - for example a mouse - as being surrounded by a world of its own - the world conveyed by its own special senses organs, and processed by its own interpretative systems. Obviously, the Umwelt will differ greatly depending on the organism. For example, bees are able to see polarized light and ultraviolet light; electric eels are able to sense their environment through their electric organs; many insects are extraordinarily sensitive to pheromones; and a dog's Umwelt far richer in smells than that of most other animals. The Umwelt of a jellyfish is very simple, but nevertheless it exists.[2] Von Uexküll's Umwelt concept can even extend to one-celled organisms, which receive chemical and tactile signals from their environment, and which are often sensitive to light. The ideas and research of Jakob von Uexküll inspired the later work of the Nobel Laureate ethologist Konrad Lorenz, and thus von Uexküll can be thought of as one of the founders of ethology as well as of Biosemiotics. Indeed, ethology and Biosemiotics are closely related.

Biosemiotics also values the ideas of the American anthropologist Gregory Bateson (1904-1980), who was mentioned in Chapter 7 in connection with cybernetics and with the Macy Conferences. He was married to another celebrated anthropologist, Margaret Mead, and together they applied Norbert Wiener's insights concerning feedback mechanisms to sociology, psychology and anthropology. Bateson was the originator of a famous epigrammatic definition of information: "..a difference which makes a difference" . This definition occurs in Chapter 3 of Bateson's book, Mind and Nature: A Necessary Unity, Bantam, (1980), and its context is as follows: "To produce news of a difference, i.e. information", Bateson wrote, "there must be two entities... such that news of their difference can be represented as a difference inside some information-processing entity, such as a brain or, perhaps, a computer. There is a profound and unanswerable question about the nature of these two entities that between them generate the difference which becomes information by making a difference. Clearly each alone is - for the mind and perception - a non-entity, a non-being... the sound of one hand clapping. The stuff of sensation, then, is a pair of values of some variable, presented over time to a sense organ, whose response depends on the ratio between the members of the pair."

6.6 Some personal memories of early computers

I hope that readers will forgive me if I tell them of my own personal memories of early computers:

When I arrived at Imperial College (then part of the University of London) in 1962,

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[2] It is interesting to ask to what extent the concept of Umwelt can be equated to that of consciousness. To the extent that these two concepts can be equated, von Uexküll's Umweltforschung offers us the opportunity to explore the phylogenetic evolution of the phenomenon of consciousness.

I worked with a crystallographic group that using the Mercury computer at University College to do the calculations needed to arrive at molecular structures. This gave me the chance to use Mercury to do quantum chemical calculations. I used to go over to University College with the crystallographers at night, because time on the computer was so expensive that we could only afford to use it at night. I would make a bed for myself out of three chairs in a row and would try to sleep. At 3 AM or 4 AM they would wake me up and would say "Now it's your turn".

Mercury was as big as a house, but could do far less than a modern laptop. It had 50,000 or so vacuum tubes which required cooling. The cooling system sometimes broke down, and one or another of the vacuum tubes sometimes failed, so one had to be grateful for the periods when Mercury was working. Our programs were written on punched tape in a language called CHLF3. (The letters stood for Cambridge, London, Harwell and Farnsborough, the four places that had Mercurys). After we had read the paper tape into the computer, the program was converted into a magnetic form on a rapidly rotating drum, and then checked against the original input. If it did not check, we had a so-called "drum parity", which meant that we had to stop the computer and restart it by hand, using a bewildering array of manual controls.

After finishing the work on Mercury at 6 AM or so, I would walk home, passing through the almost-deserted streets of Soho, and seeing pale-faced teenagers who had been up all night, high on amphetamines. They were sitting on the pavement near an underground station, waiting for it to open.

After we had used Mercury for two years or so, IBM gave Imperial College one of their early computers. Using this was much better. Programs for the IBM machine were written on punched cards. We just went over to the machine with our punched cards and stood in line to have them read into the computer. Then a few minutes later we were handed a printout of the output.

The IBM was much better than the machines that were available in eastern Europe, and for this reason I was contacted by Janos Ladik and his group at the Hungarian Academy of Science, who proposed a collaboration. We worked together for several years, calculating the electronic structure of a number of polypeptides and polynucleotides.

In 1965, Janos Ladik invited me to attend a meeting of quantum theorists and computer scientists from both East and West, held at a town on the Hungarian Puszta, the great Hungarian plain east of Budapest. At the meeting, Enrico Clementi spoke about computer programs that he had developed for performing *ab-initio*[3] calculation of the electronic structure of molecules. Clementi was an important IBM scientist, and he had his own laboratory with a large computer which he could use as he liked. The programs that he described to us took hundreds of hours to complete an electronic structure calculation on a single molecule.

In the question period after Clementi's lecture, someone from the audience said: "It's all right for you, Clementi. You can use hundreds of hours on a single calculation if you

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[3] *ab-initio* is a Latin expression meaning "from the beginning". Such programs are completely free of input parameters based on experiments.

Figure 6.14: **Enrico Clementi (born 1931) explained to us that microminiaturization would soon make computers hundreds of times faster, smaller and less expensive. He was completely right.**

want to, because you are sitting at IBM with your own dedicated computer. But what about the rest of us? What good are these programs to us?"

Clementi answered: "In a few years, computers will be hundreds of times faster, and they will also be cheaper." The audience asked: "And how will this happen?". Clementi answered: "Through microminiaturization." He was completely right. That was exactly what happened.

6.7 The invention of transistors

Microelectronics

The problem of unreliable vacuum tubes was solved in 1948 by John Bardeen, William Shockley and Walter Brattain of the Bell Telephone Laboratories. Application of quantum theory to solids had lead to an understanding of the electrical properties of crystals. Like atoms, crystals were found to have allowed and forbidden energy levels.

The allowed energy levels for an electron in a crystal were known to form bands, i.e., some energy ranges with many allowed states (allowed bands), and other energy ranges with none (forbidden bands). The lowest allowed bands were occupied by electrons, while higher bands were empty. The highest filled band was called the "valence band", and the lowest empty band was called the "conduction band".

According to quantum theory, whenever the valence band of a crystal is only partly filled, the crystal is a conductor of electricity; but if the valence band is completely filled with electrons, the crystal is an electrical insulator. (A completely filled band is analogous to a room so packed with people that none of them can move.)

In addition to conductors and insulators, quantum theory predicted the existence of "semiconductors" - crystals where the valence band is completely filled with electrons, but where the energy gap between the conduction band and the valence band is very small. For example, crystals of the elements silicon and germanium are semiconductors. For such a crystal, thermal energy is sometimes enough to lift an electron from the valence band to the conduction band.

Bardeen, Shockley and Brattain found ways to control the conductivity of germanium crystals by injecting electrons into the conduction band, or alternatively by removing electrons from the valence band. They could do this by "doping" the crystals with appropriate impurities, or by injecting electrons with a special electrode. The semiconducting crystals whose conductivity was controlled in this way could be used as electronic valves, in place of vacuum tubes.

By the 1960's, replacement of vacuum tubes by transistors in electronic computers had led not only to an enormous increase in reliability and a great reduction in cost, but also to an enormous increase in speed. It was found that the limiting factor in computer speed was the time needed for an electrical signal to propagate from one part of the central processing unit to another. Since electrical impulses propagate with the speed of light, this time is extremely small; but nevertheless, it is the limiting factor in the speed of electronic computers.

6.8 The Traitorous Eight

According to the Wikipedia article on Shockley,

"In 1956 Shockley moved from New Jersey to Mountain View, California to start Shockley Semiconductor Laboratory to live closer to his ailing mother in Palo Alto, California. The company, a division of Beckman Instruments, Inc., was the first establishment working on silicon semiconductor devices in what came to be known as Silicon Valley.

"His way [of leading the group] could generally be summed up as domineering and increasingly paranoid. In one well-known incident, he claimed that a secretary's cut thumb was the result of a malicious act and he demanded lie detector tests to find the culprit, when in reality, the secretary had simply grabbed at a door handle that happened to have an exposed tack on it for the purpose of hanging paper notes on. After he received the Nobel Prize in 1956 his demeanor changed, as evidenced in his increasingly autocratic, erratic and hard-to-please management style. In late 1957, eight of Shockley's researchers, who would come to be known as the 'traitorous eight, resigned after Shockley decided not to continue research into silicon-based semiconductors. They went on to form Fairchild Semiconductor, a loss from which Shockley Semiconductor never recovered. Over the course of the next 20 years, more than 65 new enterprises would end up having employee connections back to Fairchild."

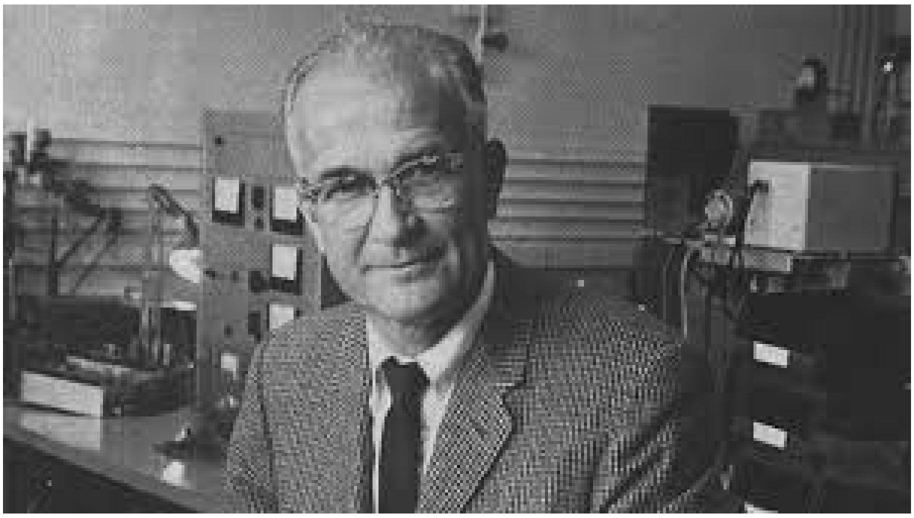


Figure 6.15: **William Shockley (1910-1989) shared the 1956 Nobel Prize in Physics with John Bardeen and Walter Brattain.**

Figure 6.16: **The Traitorous Eight: From left to right, Gordon Moore, C. Sheldon Roberts, Eugene Kleiner, Robert Noyce, Victor Grinich, Julius Blank, Jean Hoerni and Jay Last.**

6.9 Integrated circuits

In order to reduce the propagation time, computer designers tried to make the central processing units very small; and the result was the development of integrated circuits and microelectronics. (Another motive for miniaturization of electronics came from the requirements of space exploration.)

Integrated circuits were developed in which single circuit elements were not manufactured separately. Instead, the whole circuit was made at one time. An integrated circuit is a sandwich-like structure, with conducting, resisting and insulating layers interspersed with layers of germanium or silicon, "doped " with appropriate impurities. At the start of the manufacturing process, an engineer makes a large drawing of each layer. For example, the drawing of a conducting layer would contain pathways which fill the role played by wires in a conventional circuit, while the remainder of the layer would consist of areas destined to be etched away by acid.

The next step is to reduce the size of the drawing and to multiply it photographically. The pattern of the layer is thus repeated many times, like the design on a piece of wallpaper. The multiplied and reduced drawing is then focused through a reversed microscope onto the surface to be etched.

Successive layers are built up by evaporating or depositing thin films of the appropriate substances onto the surface of a silicon or germanium wafer. If the layer being made is to be conducting, the surface would consist of an extremely thin layer of copper, covered with a photosensitive layer called a "photoresist". On those portions of the surface receiving light from the pattern, the photoresist becomes insoluble, while on those areas not receiving light, the photoresist can be washed away.

The surface is then etched with acid, which removes the copper from those areas not protected by photoresist. Each successive layer of a wafer is made in this way, and finally the wafer is cut into tiny "chips", each of which corresponds to one unit of the wallpaper-like pattern.

Although the area of a chip may be much smaller than a square centimeter, the chip can contain an extremely complex circuit. A typical programmable minicomputer or "microprocessor", manufactured during the 1970's, could have 30,000 circuit elements, all of which were contained on a single chip. By 1986, more than a million transistors were being placed on a single chip.

As a result of miniaturization, the speed of computers rose steadily. In 1960, the fastest computers could perform a hundred thousand elementary operations in a second. By 1970, the fastest computers took less than a second to perform a million such operations. In 1987, a computer called GF11 was designed to perform 11 billion floating-point operations (flops) per second.

GF11 (Gigaflop 11) is a scientific parallel-processing machine constructed by IBM. Approximately ten floating-point operations are needed for each machine instruction. Thus GF11 runs at the rate of approximately a thousand million instructions per second (1,100 MIPS). The high speed achieved by parallel-processing machines results from dividing a job into many sub-jobs on which a large number of processing units can work simultaneously.

Computer memories have also undergone a remarkable development. In 1987, the magnetic disc memories being produced could store 20 million bits of information per square inch; and even higher densities could be achieved by optical storage devices. (A "bit" is the unit of information. For example, the number 25, written in the binary system, is 11001. To specify this 5-digit binary number requires 5 bits of information. To specify an n-digit binary number requires n bits of information. Eight bits make a "byte".)

In the 1970's and 1980's, computer networks were set up linking machines in various parts of the world. It became possible (for example) for a scientist in Europe to perform a calculation interactively on a computer in the United States just as though the distant machine were in the same room; and two or more computers could be linked for performing large calculations. It also became possible to exchange programs, data, letters and manuscripts very rapidly through the computer networks.

6.10 Moore's law

In 1965, only four years after the first integrated circuits had been produced, Dr. Gordon E. Moore, one of the founders of Intel, made a famous prediction which has come to be known as "Moore's Law". He predicted that the number of transistors per integrated circuit would double every two years, and that this trend would continue through 1975. In fact, the general trend predicted by Moore has continued for a much longer time. Although the number of transistors per unit area has not continued to double every two years, the logic density (bits per unit area) has done so, and thus a modified version of Moore's law still holds today. How much longer the trend can continue remains to be seen. Physical limits to miniaturization of transistors of the present type will soon be reached; but there is hope that further miniaturization can be achieved through "quantum dot" technology, molecular switches, and autoassembly.

A typical programmable minicomputer or "microprocessor", manufactured in the 1970's, could have 30,000 circuit elements, all of which were contained on a single chip. By 1989, more than a million transistors were being placed on a single chip; and by 2000, the number reached 42,000,000.

As a result of miniaturization and parallelization, the speed of computers rose exponentially. In 1960, the fastest computers could perform a hundred thousand elementary operations in a second. By 1970, the fastest computers took less than a second to perform a million such operations. In 1987, a massively parallel computer, with 566 parallel processors, called GFll was designed to perform 11 billion floating-point operations per second (flops). By 2002 the fastest computer performed 40 at teraflops, making use of 5120 parallel CPU's.

Computer disk storage has also undergone a remarkable development. In 1987, the magnetic disk storage being produced could store 20 million bits of information per square inch; and even higher densities could be achieved by optical storage devices. Storage density has until followed a law similar to Moore's law.

In the 1970's and 1980's, computer networks were set up linking machines in various

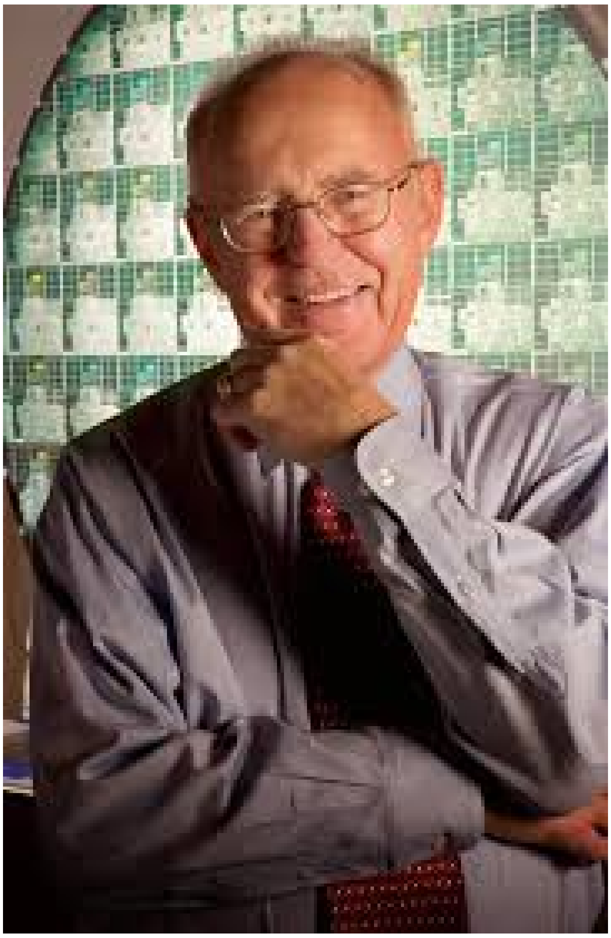
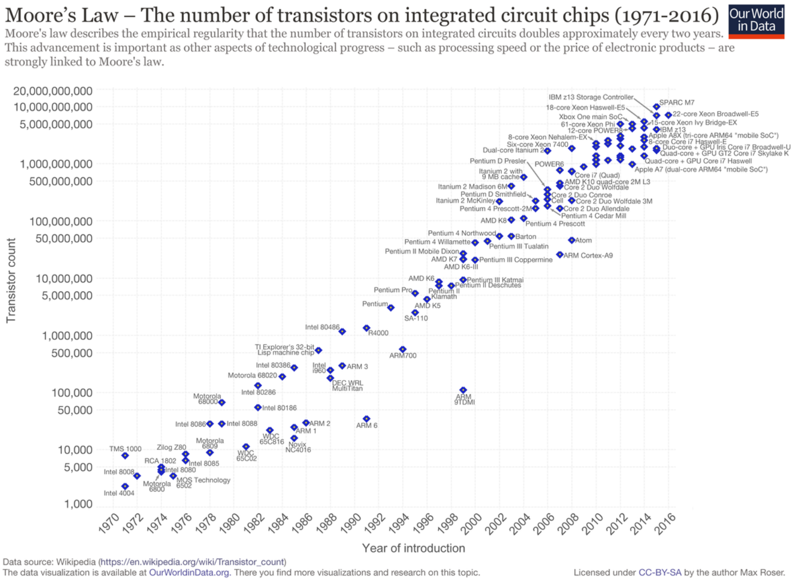


Figure 6.17: **Gordon E. Moore (born 1929), a founder of Intel and the author of Moore's Law. In 1965 he predicted that the number of components in integrated circuits would double every year for the next 10 years". In 1975 he predicted the this doubling would continue, but revised the doubling rate to "every two years. Astonishingly, Moore's Law has held much longer than he, or anyone else, anticipated.**


Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.

Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Licensed under CC-BY-SA by the author Max Roser.

Figure 6.18: **Amazingly, Moore's Law has held much longer than he, or anyone else, anticipated. Perhaps quantum dot technologies can extend its validity even longer.**

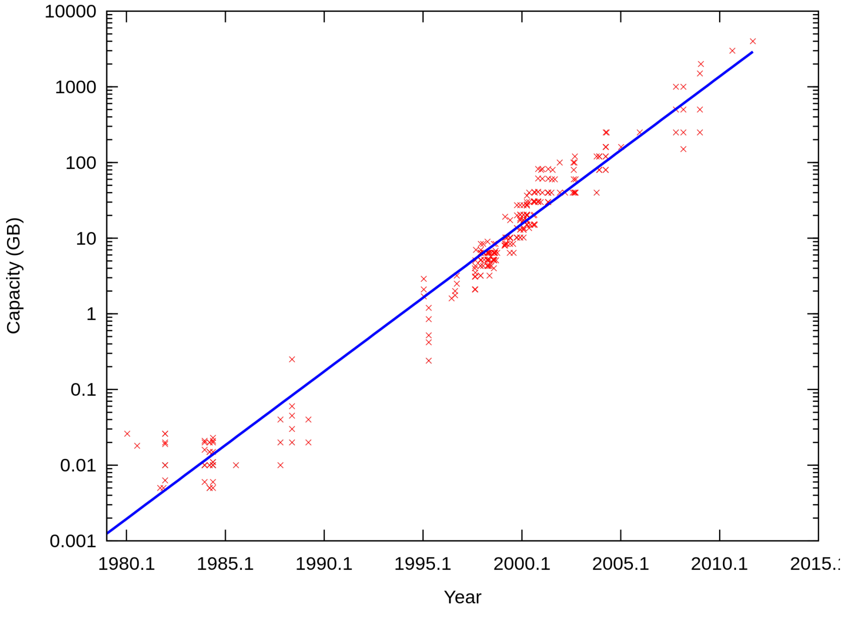


Figure 6.19: **A logarithmic plot of the increase in PC hard-drive capacity in gigabytes. An extrapolation of the rate of increase predicts that the individual capacity of a commercially available PC will reach 10,000 gigabytes by 2015, i.e. 10,000,000,000,000 bytes. (After Hankwang and Rentar, Wikimedia Commons)**

parts of the world. It became possible (for example) for a scientist in Europe to perform a calculation interactively on a computer in the United States just as though the distant machine were in the same room; and two or more computers could be linked for performing large calculations. It also became possible to exchange programs, data, letters and manuscripts very rapidly through the computer networks.

The exchange of large quantities of information through computer networks was made easier by the introduction of fiber optics cables. By 1986, 250,000 miles of such cables had been installed in the United States. If a ray of light, propagating in a medium with a large refractive index, strikes the surface of the medium at a grazing angle, then the ray undergoes total internal reflection. This phenomenon is utilized in fiber optics: A light signal can propagate through a long, hairlike glass fiber, following the bends of the fiber without losing intensity because of total internal reflection. However, before fiber optics could be used for information transmission over long distances, a technological breakthrough in glass manufacture was needed, since the clearest glass available in 1940 was opaque in lengths more than 10 m. Through studies of the microscopic properties of glasses, the problem of absorption was overcome. By 1987, devices were being manufactured commercially that were capable of transmitting information through fiber-optic cables at the rate of 1.7 billion bits per second.

6.11 Automation

During the last three decades, the cost of computing has decreased exponentially by between twenty and thirty percent per year. Meanwhile, the computer industry has grown exponentially by twenty percent per year (faster than any other industry). The astonishing speed of this development has been matched by the speed with which computers have become part of the fabric of science, engineering, industry, commerce, communications, transport, publishing, education and daily life in the industrialized parts of the world.

The speed, power and accuracy of computers has revolutionized many branches of science. For example, before the era of computers, the determination of a simple molecular structure by the analysis of X-ray diffraction data often took years of laborious calculation; and complicated structures were completely out of reach. In 1949, however, Dorothy Crowfoot Hodgkin used an electronic computer to work out the structure of penicillin from X-ray data. This was the first application of a computer to a biochemical problem; and it was followed by the analysis of progressively larger and more complex structures.

Proteins, DNA, and finally even the detailed structures of viruses were studied through the application of computers in crystallography. The enormous amount of data needed for such studies was gathered automatically by computer-controlled diffractometers; and the final results were stored in magnetic-tape data banks, available to users through computer networks.

The application of quantum theory to chemical problems is another field of science which owes its development to computers. When Erwin Schrödinger wrote down his wave equation in 1926, it became possible, in principle, to calculate most of the physical and chemical properties of matter. However, the solutions to the Schrödinger equation for many-particle systems can only be found approximately; and before the advent of computers, even approximate solutions could not be found, except for the simplest systems.

When high-speed electronic digital computers became widely available in the 1960's, it suddenly became possible to obtain solutions to the Schrödinger equation for systems of chemical and even biochemical interest. Quantum chemistry (pioneered by such men as J.C. Slater, R.S. Mullikin, D.R. Hartree, V. Fock, J.H. Van Vleck, L. Pauling, E.B. Wilson, P.O. Löwdin, E. Clementi, C.J. Ballhausen and others) developed into a rapidly-growing field, as did solid state physics. Through the use of computers, it became possible to design new materials with desired chemical, mechanical, electrical or magnetic properties. Applying computers to the analysis of reactive scattering experiments, D. Herschbach, J. Polanyi and Y. Lee were able to achieve an understanding of the dynamics of chemical reactions.

The successes of quantum chemistry led Albert Szent-Györgyi, A. and B. Pullman, H. Scheraga and others to pioneer the fields of quantum biochemistry and molecular dynamics. Computer programs for drug design were developed, as well as molecular-dynamics programs which allowed the conformations of proteins to be calculated from a knowledge of their amino acid sequences. Studies in quantum biochemistry have yielded insights into the mechanisms of enzyme action, photosynthesis, active transport of ions across membranes, and other biochemical processes.

In medicine, computers began to be used for monitoring the vital signs of critically ill patients, for organizing the information flow within hospitals, for storing patients' records, for literature searches, and even for differential diagnosis of diseases.

The University of Pennsylvania has developed a diagnostic program called INTERNIST-1, with a knowledge of 577 diseases and their interrelations, as well as 4,100 signs, symptoms and patient characteristics. This program was shown to perform almost as well as an academic physician in diagnosing difficult cases. QMR (Quick Medical Reference), a microcomputer adaptation of INTERNIST-1, incorporates the diagnostic functions of the earlier program, and also offers an electronic textbook mode.

Beginning in the 1960's, computers played an increasingly important role in engineering and industry. For example, in the 1960's, Rolls Royce Ltd. began to use computers not only to design the optimal shape of turbine blades for aircraft engines, but also to control the precision milling machines which made the blades. In this type of computer-assisted design and manufacture, no drawings were required. Furthermore, it became possible for an industry requiring a part from a subcontractor to send the machine-control instructions for its fabrication through the computer network to the subcontractor, instead of sending drawings of the part.

In addition to computer-controlled machine tools, robots were also introduced. They were often used for hazardous or monotonous jobs, such as spray-painting automobiles; and they could be programmed by going through the job once manually in the programming mode. By 1987, the population of robots in the United States was between 5,000 and 7,000, while in Japan, the Industrial Robot Association reported a robot population of 80,000.

Chemical industries began to use sophisticated computer programs to control and to optimize the operations of their plants. In such control systems, sensors reported current temperatures, pressures, flow rates, etc. to the computer, which then employed a mathematical model of the plant to calculate the adjustments needed to achieve optimum operating conditions.

Not only industry, but also commerce, felt the effects of computerization during the postwar period. Commerce is an information-intensive activity; and in fact some of the crucial steps in the development of information-handling technology developed because of the demands of commerce: The first writing evolved from records of commercial transactions kept on clay tablets in the Middle East; and automatic business machines, using punched cards, paved the way for the development of the first programmable computers.

Computerization has affected wholesaling, warehousing, retailing, banking, stockmarket transactions, transportation of goods - in fact, all aspects of commerce. In wholesaling, electronic data is exchanged between companies by means of computer networks, allowing order-processing to be handled automatically; and similarly, electronic data on prices is transmitted to buyers.

The key to automatic order-processing in wholesaling was standardization. In the United States, the Food Marketing Institute, the Grocery Manufacturers of America, and several other trade organizations, established the Uniform Communications System (UCS) for the grocery industry. This system specifies a standard format for data on products, prices and orders.

Automatic warehouse systems were designed as early as 1958. In such systems, the goods to be stored are placed on pallets (portable platforms), which are stacked automatically in aisles of storage cubicles. A computer records the position of each item for later automatic retrieval.

In retailing, just as in wholesaling, standardization proved to be the key requirement for automation. Items sold in supermarkets in most industrialized countries are now labeled with a standard system of machine-readable thick and thin bars known as the Universal Product Code (UPC). The left-hand digits of the code specify the manufacturer or packer of the item, while the right-hand set of digits specify the nature of the item. A final digit is included as a check, to make sure that the others were read correctly. This last digit (called a modulo check digit) is the smallest number which yields a multiple of ten when added to the sum of the previous digits.

When a customer goes through a check-out line, the clerk passes the purchased items over a laser beam and photocell, thus reading the UPC code into a small embedded computer or microprocessor at the checkout counter, which adds the items to the customer's bill. The microprocessor also sends the information to a central computer and inventory data base. When stocks of an item become low, the central computer generates a replacement order. The financial book-keeping for the retailing operation is also carried out automatically by the central computer.

In many places, a customer passing through the checkout counter of a supermarket is able to pay for his or her purchases by means of a plastic card with a magnetic, machine-readable identification number. The amount of the purchase is then transmitted through a computer network and deducted automatically from the customer's bank account. If the customer pays by check, the supermarket clerk may use a special terminal to determine whether a check written by the customer has ever "bounced".

Most checks are identified by a set of numbers written in the Magnetic-Ink Character Recognition (MICR) system. In 1958, standards for the MICR system were established, and by 1963, 85 percent of all checks written in the United States were identified by MICR numbers. By 1968, almost all banks had adopted this system; and thus the administration of checking accounts was automated, as well as the complicated process by which a check, deposited anywhere in the world, returns to the payers bank.

Container ships were introduced in the late 1950's, and since that time, container systems have increased cargo-handling speeds in ports by at least an order of magnitude. Computer networks contributed greatly to the growth of the container system of transportation by keeping track of the position, ownership and contents of the containers.

In transportation, just as in wholesaling and retailing, standardization proved to be a necessary requirement for automation. Containers of a standard size and shape could be loaded and unloaded at ports by specialized tractors and cranes which required only a very small staff of operators. Standard formats for computerized manifests, control documents, and documents for billing and payment, were instituted by the Transportation Data Coordinating Committee, a non-profit organization supported by dues from shipping firms.

In the industrialized parts of the world, almost every type of work has been made more efficient by computerization and automation. Even artists, musicians, architects and authors find themselves making increasing use of computers: Advanced computing systems, using specialized graphics chips, speed the work of architects and film animators. The author's traditional typewriter has been replaced by a word-processor, the composer's piano by a music synthesizer.

In the Industrial Revolution of the 18th and 19th centuries, muscles were replaced by machines. Computerization represents a Second Industrial Revolution: Machines have begun to perform not only tasks which once required human muscles, but also tasks which formerly required human intelligence.

In industrial societies, the mechanization of agriculture has very much reduced the fraction of the population living on farms. For example, in the United States, between 1820 and 1980, the fraction of workers engaged in agriculture fell from 72 percent to 3.1 percent. There are signs that computerization and automation will similarly reduce the number of workers needed in industry and commerce.

Computerization is so recent that, at present, we can only see the beginnings of its impact; but when the Second Industrial Revolution is complete, how will it affect society? When our children finish their education, will they face technological unemployment?

The initial stages of the First Industrial Revolution produced much suffering, because labor was regarded as a commodity to be bought and sold according to the laws of supply and demand, with almost no consideration for the needs of the workers. Will we repeat this mistake? Or will society learn from its earlier experience, and use the technology of automation to achieve widely-shared human happiness?

The Nobel-laureate economist, Wassily W. Leontief, has made the following comment on the problem of technological unemployment:

"Adam and Eve enjoyed, before they were expelled from Paradise, a high standard of living without working. After their expulsion, they and their successors were condemned to eke out a miserable existence, working from dawn to dusk. The history of technological progress over the last 200 years is essentially the story of the human species working its way slowly and steadily back into Paradise. What would happen, however, if we suddenly found ourselves in it? With all goods and services provided without work, no one would be gainfully employed. Being unemployed means receiving no wages. As a result, until appropriate new income policies were formulated to fit the changed technological conditions, everyone would starve in Paradise."

To say the same thing in a slightly different way: consider what will happen when a factory which now employs a thousand workers introduces microprocessor-controlled industrial robots and reduces its work force to only fifty. What will the nine hundred and fifty redundant workers do? They will not be able to find jobs elsewhere in industry, commerce or agriculture, because all over the economic landscape, the scene will be the same.

There will still be much socially useful work to be done - for example, taking care of elderly people, beautifying the cities, starting youth centers, planting forests, cleaning up pollution, building schools in developing countries, and so on. These socially beneficial goals are not commercially "profitable". They are rather the sort of projects which governments sometimes support if they have the funds for it. However, the money needed to usefully employ the nine hundred and fifty workers will not be in the hands of the government. It will be in the hands of the factory owner who has just automated his production line.

In order to make the economic system function again, either the factory owner will have to be persuaded to support socially beneficial but commercially unprofitable projects, or else an appreciable fraction of his profits will have to be transferred to the government, which will then be able to constructively re-employ the redundant workers.

The future problems of automation and technological unemployment may force us to rethink some of our economic ideas. It is possible that helping young people to make a smooth transition from education to secure jobs will become one of the important responsibilities of governments, even in countries whose economies are based on free enterprise. If such a change does take place in the future, while at the same time socialistic countries are adopting a few of the better features of free enterprise, then one can hope that the world will become less sharply divided by contrasting economic systems.

The history of the Internet and World Wide Web

The history of the Internet began in 1961, when Leonard Kleinrock, a student at MIT, submitted a proposal for Ph.D. thesis entitled "Information Flow in Large Communication Nets". In his statement of the problem, Kleinrock wrote: "The nets under consideration consist of nodes, connected to each other by links. The nodes receive, sort, store, and transmit messages that enter and leave via the links. The links consist of one-way channels, with fixed capacities. Among the typical systems which fit this description are the Post Office System, telegraph systems, and satellite communication systems." Kleinrock's theoretical treatment of package switching systems anticipated the construction of computer networks which would function on a principle analogous to a post office rather than a telephone exchange: In a telephone system, there is a direct connection between the sender and receiver of information. But in a package switching system, there is no such connection - only the addresses of the sender and receiver on the package of information, which makes its way from node to node until it reaches its destination.

Further contributions to the concept of package switching systems and distributed communications networks were made by J.C.R. Licklider and W. Clark of MIT in 1962, and by Paul Baran of the RAND corporation in 1964. Licklider visualized what he called a "Galactic Network", a globally interconnected network of computers which would allow social interactions and interchange of data and software throughout the world. The distributed computer communication network proposed by Baran was motivated by the desire to have a communication system that could survive a nuclear war. The Cold War had also provoked the foundation (in 1957) of the Advanced Research Projects Agency (ARPA) by the U.S. government as a response to the successful Russian satellite "Sputnik".

In 1969, a 4-node network was tested by ARPA. It connected computers at the University of California divisions at Los Angeles and Santa Barbara with computers at the Stanford Research Institute and the University of Utah. Describing this event, Leonard Kleinrock said in an interview: "We set up a telephone connection between us and the guys at SRI. We typed the L and we asked on the phone 'Do you see the L?' 'Yes we see the L', came the response. We typed the 0 and we asked 'Do you see the 0?' 'Yes we see the O.' Then we typed the G and the system crashed." The ARPANET (with 40 nodes) performed much better in 1972 at the Washington Hilton Hotel where the participants at a Conference on Computer Communications were invited to test it.

Although the creators of ARPANET visualized it as being used for long- distance computations involving several computers, they soon discovered that social interactions over the Internet would become equally important if not more so. An electronic mail system was introduced in the early 1970's, and in 1976 Queen Elizabeth II of the United Kingdom became one of the increasing number of e-mail users.

In September, 1973, Robert F. Kahn and Vinton Cerf presented the basic ideas of the Internet at a meeting of the International Network Working Group at the University Sussex in Brighton, England. Among these principles was the rule that the networks to be connected should not be changed internally. Another rule was that if a packet did not arrive at its destination, it would be retransmitted from its original source. No information was to be retained by the gateways used to connect networks; and finally there was to be no global control of the Internet at the operations level.

Computer networks devoted to academic applications were introduced in the 1970's and 1980's, both in England, the United States and Japan. The Joint Academic Network (JANET) in the U.K. had its counterpart in the National Science Foundation's network (NSFNET) in America and Japan's JUNET (Japan Unix Network). Internet traffic is

Table 6.1: **Historical total world Internet traffic (after Cisco Visual Networking Index Forecast). 1 terrabyte =1,000,000,000,000 bytes**

year	terabytes per month
1990	1
1991	2
1992	4
1993	10
1994	20
1995	170
1996	1,800
1997	5,000
1998	11,000
1999	26,000
2000	75,000
2001	175,000
2002	358,000
2003	681,000
2004	1,267,000
2005	2,055,000
2006	3,339,000
2007	5,219,000
2008	7,639,000
2009	10,676,000
2010	14,984,000

approximately doubling each year,[4] and it is about to overtake voice communication in the volume of information transferred.

In March, 2011, there were more than two billion Internet users in the world. In North America they amounted to 78.3 % of the total population, in Europe 58.3 % and worldwide, 30.2 %. Another index that can give us an impression of the rate of growth of digital data generation and exchange is the “digital universe”, which is defined to be the total volume of digital information that human information technology creates and duplicates in a year. In 2011 the digital universe reached 1.2 zettabytes, and it is projected to quadruple by 2015. A zettabyte is 10^{21} bytes, an almost unimaginable number, equivalent to the information contained in a thousand trillion books, enough books to make a pile that would stretch twenty billion kilometers.

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[4] In the period 1995-1996, the rate of increase was even faster - a doubling every four months

Self-reinforcing information accumulation

Humans have been living on the earth for roughly two million years (more or less, depending on where one draws the line between our human and prehuman ancestors, Table 6.1). During almost all of this,time, our ancestors lived by hunting and food-gathering. They were not at all numerous, and did not stand out conspicuously from other animals. Then, suddenly, during the brief space of ten thousand years, our species exploded in numbers from a few million to seven billion (Figure 6.1), populating all parts of the earth, and even setting foot on the moon. This population explosion, which is still going on, has been the result of dramatic cultural changes. Genetically we are almost identical with our hunter-gatherer ancestors, who lived ten thousand years ago, but cultural evolution has changed our way of life beyond recognition.

Beginning with the development of speech, human cultural evolution began to accelerate. It started to move faster with the agricultural revolution, and faster still with the invention of writing and printing. Finally, modern science has accelerated the rate of social and cultural change to a completely unprecedented speed.

The growth of modern science is accelerating because knowledge feeds on itself. A new idea or a new development may lead to several other innovations, which can in turn start an avalanche of change. For example, the quantum theory of atomic structure led to the invention of transistors, which made high-speed digital computers possible. Computers have not only produced further developments in quantum theory; they have also revolutionized many other fields.

The self-reinforcing accumulation of knowledge - the information explosion - which characterizes modern human society is reflected not only in an explosively-growing global population, but also in the number of scientific articles published, which doubles roughly every ten years. Another example is Moore's law - the doubling of the information density of integrated circuits every two years. Yet another example is the explosive growth of Internet traffic shown in Table 7.1.

The Internet itself is the culmination of a trend towards increasing societal information exchange - the formation of a collective human consciousness. This collective consciousness preserves the observations of millions of eyes, the experiments of millions of hands, the thoughts of millions of brains; and it does not die when the individual dies.

6.12 Neural networks

Physiologists have begun to make use of insights derived from computer design in their efforts to understand the mechanism of the brain; and computer designers are beginning to construct computers modeled after neural networks. We may soon see the development of computers capable of learning complex ideas, generalization, value judgements, artistic creativity, and much else that was once thought to be uniquely characteristic of the human mind. Efforts to design such computers will undoubtedly give us a better understanding of the way in which the brain performs its astonishing functions.

Much of our understanding of the nervous systems of higher animals is due to the Spanish microscopist, Ramón y Cajal, and to the English physiologists, Alan Hodgkin and Andrew Huxley. Cajal's work, which has been confirmed and elaborated by modern electron microscopy, showed that the central nervous system is a network of nerve cells (neurons) and threadlike fibers growing from them. Each neuron has many input fibers (dendrites), and one output fiber (the axon), which may have several branches.

It is possible the computers of the future will have pattern-recognition and learning abilities derived from architecture inspired by our understanding of the synapse, by Young's model, or by other biological models. However, pattern recognition and learning can also be achieved by programming, using computers of conventional architecture. Programs already exist which allow computers to understand both handwriting and human speech; and a recent chess-playing program was able to learn by studying a large number of championship games. Having optimized its parameters by means of this learning experience, the chess-playing program was able to win against grand masters!

Like nuclear physics and genesplicing, artificial intelligence presents a challenge: Will society use its new powers wisely and humanely? The computer technology of the future can liberate us from dull and repetitive work, and allow us to use our energies creatively; or it can produce unemployment and misery, depending on how we organize our society. Which will we choose?

The merging of information technology and biotechnology

Information technology and biology are today the two most rapidly developing fields of science. Interestingly, these two fields seem to be merging, each gaining inspiration and help from the other. For example, computer scientists designing both hardware and software are gaining inspiration from physiological studies of the mechanism of the brain; and conversely, neurophysiologists are aided by insights from the field of artificial intelligence. Designers of integrated circuits wish to prolong the period of validity of Moore's law; but they are rapidly approaching physical barriers which will set limits to the miniaturization of conventional transistors and integrated circuits. They gain inspiration from biology, where the language of molecular complementarity and the principle of autoassembly seem to offer hope that molecular switches and self-assembled integrated circuits may one day be constructed.

Geneticists, molecular biologists, biochemists and crystallographers have now obtained so much information about the amino acid sequences and structures of proteins and about the nucleotide sequences in genomes that the full power of modern information technology is needed to store and to analyze this information. Computer scientists, for their part, turn to evolutionary genetics for new and radical methods of developing both software and hardware - genetic algorithms and simulated evolution.

Self-assembly of supramolecular structures; Nanoscience

One of the best studied examples of autoassembly through the mechanism of molecular complementarity is the tobacco mosaic virus. The assembled virus has a cylindrical form about 300 nm long (1 nm = 1 nanometer = 10^{-9} meters = 10 Ångstroms), with a width of 18 nm. The cylindrically shaped virus is formed from about 2000 identical protein molecules. These form a package around an RNA molecule with a length of approximately 6400 nucleotides. The tobacco mosaic virus can be decomposed into its constituent molecules in vitro, and the protein and RNA can be separated and put into separate bottles.

If, at a later time, one mixes the protein and RNA molecules together in solution, they spontaneously assemble themselves into new infective tobacco mosaic virus particles. The mechanism for this spontaneous autoassembly is a random motion of the molecules through the solvent until they approach each other in such a way that a fit is formed. When two molecules fit closely together, with their physical contours matching, and with complementary patterns of excess charge also matching, the Gibbs free energy of the total system is minimized. Thus the self-assembly of matching components proceeds spontaneously, just as every other chemical reaction proceeds spontaneously when the difference in Gibbs free energy between the products and reactants is negative. The process of autoassembly is analogous to crystallization, except that the structure formed is more complex than an ordinary crystal.

A second very well-studied example of biological autoassembly is the spontaneous formation of bilayer membranes when phospholipid molecules are shaken together in water. Each phospholipid molecule has a small polar (hydrophilic) head, and a long nonpolar (hydrophobic) tail. The polar head is hydrophilic - water-loving - because it has large excess charges with which water can form hydrogen bonds. By contrast, the non-polar tail of a phospholipid molecule has no appreciable excess charges. The tail is hydrophobic - it hates water - because to fit into the water structure it has to break many hydrogen bonds to make a hole for itself, but it cannot pay for these broken bonds by forming new hydrogen bonds with water.

There is a special configuration of the system of water and phospholipid molecules which has a very low Gibbs free energy - the lipid bilayer. In this configuration, all the hydrophilic polar heads are in contact with water, while the hydrophobic nonpolar tails are in the interior of the double membrane, away from the water, and in close contact with each other, thus maximizing their mutual Van der Waals attractions. (The basic structure of biological membranes is the lipid bilayer just described, but there are also other components, such as membrane-bound proteins, caveolae, and ion pores.)

The mechanism of self-organization of supramolecular structures is one of the most important universal mechanisms of biology. Chemical reactions take place spontaneously when the change in Gibbs free energy produced by the reaction is negative, i.e., chemical reactions take place in such a direction that the entropy of the universe increases. When spontaneous chemical reactions take place, the universe moves from a less probable configuration to a more probable one. The same principle controls the motion of larger systems, where molecules arrange themselves spontaneously to form supramolecular structures. Self-assembling collections of molecules move in such a way as to minimize their Gibbs free energy, thus maximizing the entropy of the universe.

Biological structures of all kinds are formed spontaneously from their components because assembly information is written onto their joining surfaces in the form of complementary surface contours and complementary patterns of excess charge[5]. Matching pieces fit together, and the Gibbs free energy of the system is minimized. Virtually every structure observed in biology is formed in this way - by a process analogous to crystallization, except that biological structures can be far more complex than ordinary crystals.

Researchers in microelectronics, inspired by the self-assembly of biological structures, dream of using the same principles to generate self-organizing integrated circuits with features so small as to approach molecular dimensions. The speed of a computing operation is limited by the time that it takes an electrical signal (moving at approximately the speed of light) to traverse a processing unit. The desire to produce ever greater computation speeds as well as ever greater memory densities, motivates the computer industry's drive towards ultraminiaturization.

Currently the fineness of detail in integrated circuits is limited by diffraction effects caused by the finite wavelength of the light used to project an image of the circuit onto a layer of photoresist covering the chip where the circuit is being built up. For this reason, there is now very active research on photolithography using light sources with extremely short wavelengths, in the deep ultraviolet, or even X-ray sources, synchrotron radiation, or electron beams. The aim of this research is to produce integrated circuits whose feature size is in the nanometer range - smaller than 100 nm. In addition to these efforts to create nanocircuits by "top down" methods, intensive research is also being conducted on "bottom up" synthesis, using principles inspired by biological self-assembly. The hope to make use of "the spontaneous association of molecules, under equilibrium conditions, into stable, structurally well-defined aggregates, joined by non-covalent bonds"[6]

The Nobel Laureate Belgian chemist J.-M. Lehn pioneered the field of supramolecular chemistry by showing that it is possible to build nanoscale structures of his own design. Lehn and his coworkers at the University of Strasbourg used positively-charged metal ions as a kind of glue to join larger structural units at points where the large units exhibited excess negative charges. Lehn predicts that the supramolecular chemistry of the future will follow the same principles of self-organization which underlie the growth of biological structures, but with a greatly expanded repertory, making use of elements (such as silicon) that are not common in carbon-based biological systems.

Other workers in nanotechnology have concentrated on the self-assembly of two-dimensional structures at water-air interfaces. For example, Thomas Bjørnholm, working at the University of Copenhagen, has shown that a nanoscale wire can be assembled spontaneously at a water-air interface, using metal atoms complexed with DNA and a DNA template. The use of a two-dimensional template to reproduce a nanostructure can be thought of as "microprinting". One can also think of self-assembly at surfaces as the two-dimensional version

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[5] Patterns of reactive or polarizable groups also play a role.

[6] G.M. Whiteside et al., Science, **254**, 1312-1314, (1991).

of the one-dimensional copying process by which a new DNA or RNA strand assembles itself spontaneously, guided by the complementary strand.

In 1981, Gerd Binning and Heinrich Rohrer of IBM's Research Center in Switzerland announced their invention of the scanning tunneling microscope. The new microscope's resolution was so great that single atoms could be observed. The scanning tunneling microscope consists of a supersharp conducting tip, which is brought near enough to a surface so that quantum mechanical tunneling of electrons can take place between tip and surface when a small voltage is applied. The distance between the supersharp tip and the surface is controlled by means of a piezoelectric crystal. As the tip is moved along the surface, its distance from the surface (and hence the tunneling current) is kept constant by applying a voltage to the piezoelectric crystal, and this voltage as a function of position gives an image of the surface.

Variations on the scanning tunneling microscope allow single atoms to be deposited or manipulated on a surface. Thus there is a hope that nanoscale circuit templates can be constructed by direct manipulation of atoms and molecules, and that the circuits can afterwards be reproduced using autoassembly mechanisms.

The scanning tunneling microscope makes use of a quantum mechanical effect: Electrons exhibit wavelike properties, and can tunnel small distances into regions of negative kinetic energy - regions which would be forbidden to them by classical mechanics. In general it is true that for circuit elements with feature sizes in the nanometer range, quantum effects become important. For conventional integrated circuits, the quantum effects which are associated with this size-range would be a nuisance, but workers in nanotechnology hope to design integrated circuits which specifically make use of these quantum effects.

Molecular switches; bacteriorhodopsin

The purple, salt-loving archaebacterium Halobacterium halobium (recently renamed Halobacterium salinarum) possesses one of the simplest structures that is able to perform photosynthesis. The purple membrane subtraction of this bacterium's cytoplasmic membrane contains only two kinds of molecules - lipids and bacteriorhodopsin. Nevertheless, this simple structure is able to trap the energy of a photon from the sun and to convert it into chemical energy.

The remarkable purple membrane of Halobacterium has been studied in detail by Walter Stoeckenius, D. Osterhelt[7], Lajos Keszthelyi and others.

It can be decomposed into its constituent molecules. The lipids from the membrane and the bacteriorhodopsin can be separated from each other and put into different bottles. At a later time, the two bottles can be taken from the laboratory shelf, and their contents can be shaken together in water. The result is the spontaneous formation of tiny vesicles of purple membrane.

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[7] D. Osterhelt and Walter Stoeckenius, Nature New Biol. **233**, 149-152 (1971); D. Osterhelt et al., Quart. Rev. Biophys. **24**, 425-478 (1991); W. Stoeckenius and R. Bogomolni, Ann. Rev. Biochem. **52**, 587-616 (1982).

In the self-organized two-component vesicles, the membrane-bound protein bacteriorhodopsin is always correctly oriented, just as it would be in the purple membrane of a living Halobacterium. When the vesicles are illuminated, bacteriorhodopsin absorbs H^+ ions from the water on the inside, and releases them outside.

Bacteriorhodopsin consists of a chain of 224 amino acids, linked to the retinal chromophore. The amino acids are arranged in 7 helical segments, each of which spans the purple membrane, and these are joined on the membrane surface by short nonhelical segments of the chain. The chromophore is in the middle of the membrane, surrounded by a-helical segments. When the chromophore is illuminated, its color is temporarily bleached, and it undergoes a cis-trans isomerization which disrupts the hydrogen-bonding network of the protein. The result is that a proton is released on the outside of the membrane. Later, a proton is absorbed from the water in the interior of the membrane vesicle, the hydrogen-bonding system of the protein is reestablished, and both the protein and the chromophore return to their original conformations. In this way, bacteriorhodopsin functions as a proton pump. It uses the energy of photons to transport H^+ ions across the membrane, from the inside to the outside, against the electrochemical gradient. In the living Halobacterium, this H^+ concentration difference would be used to drive the synthesis of the high-energy phosphate bond of adenosine triphosphate (ATP), the inward passage of H^+ through other parts of the cytoplasmic membrane being coupled to the reaction $ADP + P_i \rightarrow ATP$ by membrane-bound reversible ATPase.

Bacteriorhodopsin is interesting as a component of one of the simplest known photosynthetic systems, and because of its possible relationship to the evolution of the eye. In addition, researchers like Lajos Keszthelyi at the Institute of Biophysics of the Hungarian Academy of Sciences in Szeged are excited about the possible use of bacteriorhodopsin in optical computer memories[8]. Arrays of oriented and partially dehydrated bacteriorhodopsin molecules in a plastic matrix can be used to construct both 2-dimensional and 3-dimensional optical memories using the reversible color changes of the molecule. J. Chen and coworkers[9] have recently constructed a prototype 3-dimensional optical memory by orienting the proteins and afterwards polymerizing the solvent into a solid polyacrylamide matrix. Bacteriorhodopsin has extraordinary stability, and can tolerate as many as a million optical switching operations without damage.

Neural networks, biological and artificial

In 1943, W. McCulloch and W. Pitts published a paper entitled *A Logical Calculus of the Ideas Immanent in Nervous Activity.* In this pioneering paper, they proposed the idea of a Threshold Logic Unit (TLU), which they visualized not only as a model of the way in which neurons function in the brain but also as a possible subunit for artificial systems which might be constructed to perform learning and pattern-recognition tasks. Problems involving learning, generalization, pattern recognition and noisy data are easily handled

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[8] A. Der and L. Keszthelyi, editors, Bioelectronic Applications of Photochromic Pigments, IOS Press, Amsterdam, Netherlands, (2001).

[9] J. Chen et al., Biosystems **35**, 145-151 (1995).

by the brains of humans and animals, but computers of the conventional von Neumann type find such tasks especially difficult.

Conventional computers consist of a memory and one or more central processing units (CPUs). Data and instructions are repeatedly transferred from the memory to the CPUs, where the data is processed and returned to the memory. The repeated performance of many such cycles requires a long and detailed program, as well as high-quality data. Thus conventional computers, despite their great speed and power, lack the robustness, intuition, learning powers and powers of generalization which characterize biological neural networks. In the 1950's, following the suggestions of McCulloch and Pitts, and inspired by the growing knowledge of brain structure and function which was being gathered by histologists and neurophysiologists, computer scientists began to construct artificial neural networks - massively parallel arrays of TLU's.

The analogy between a TLU and a neuron can be seen by comparing Figure 5.2, which shows a neuron, with Figure 8.1, which shows a TLU. A neuron is a specialized cell consisting of a cell body (*soma*) from which an extremely long, tubelike fiber called an *axon* grows. The axon is analogous to the output channel of a TLU. From the soma, a number of slightly shorter, rootlike extensions called *dendrites* also grow. The dendrites are analogous to the input channels of a TLU.

In a biological neural network, branches from the axon of a neuron are connected to the dendrites of many other neurons; and at the points of connection there are small, knoblike structures called synapses. The "firing" of a neuron sends a wave of depolarization out along its axon. When the pulselike electrical and chemical disturbance associated with the wave of depolarization (the action potential) reaches a synapse, where the axon is connected with another neuron, transmitter molecules are released into the post-synaptic cleft. The neurotransmitter molecules travel across the post-synaptic cleft to receptors on a dendrite of the next neuron in the net, where they are bound to receptors. There are many kinds of neurotransmitter molecules, some of which tend to make the firing of the next neuron more probable, and others which tend to inhibit its firing. When the neurotransmitter molecules are bound to the receptors, they cause a change in the dendritic membrane potential, either increasing or decreasing its polarization. The post-synaptic potentials from the dendrites are propagated to the soma; and if their sum exceeds a threshold value, the neuron fires. The subtlety of biological neural networks derives from the fact that there are many kinds of neurotransmitters and synapses, and from the fact that synapses are modified by their past history.

Turning to Figure 8.1, we can compare the biological neuron with the Threshold Logic Unit of McCulloch and Pitts. Like the neuron, the TLU has many input channels. To each of the N channels there is assigned a weight, $w_1, w_2, ..., w_N$. The weights can be changed; and the set of weights gives the TLU its memory and learning capabilities. Modification of weights in the TLU is analogous to the modification of synapses in a neuron, depending on their history. In the most simple type of TLU, the input signals are either 0 or 1. These signals, multiplied by their appropriate weights, are summed, and if the sum exceeds a threshold value, θ the TLU "fires", i.e. a pulse of voltage is transmitted through the output channel to the next TLU in the artificial neural network.

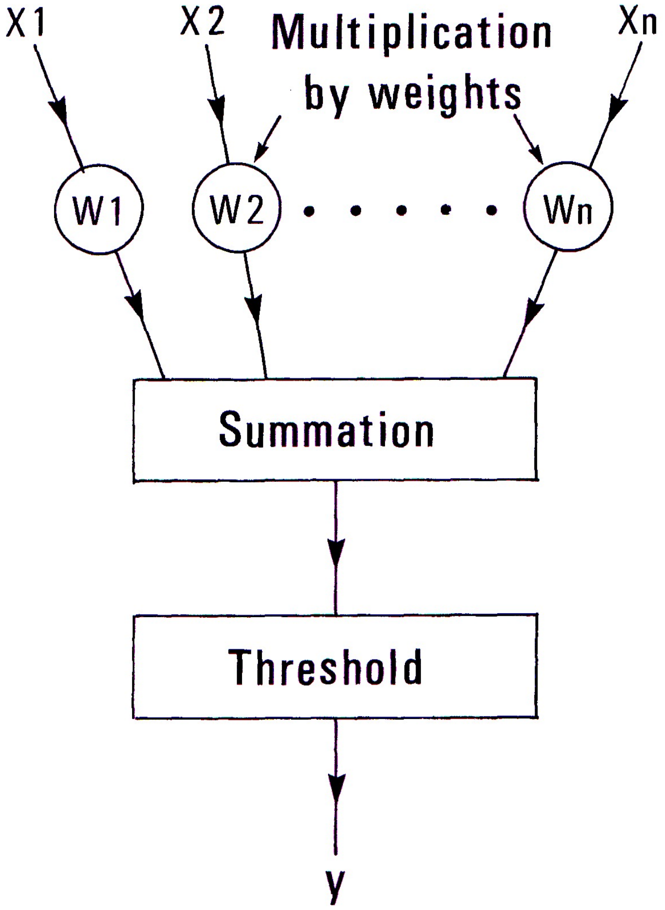

Figure 6.20: A Threshold Logic Unit (TLU) of the type proposed by McCulloch and Pitts.

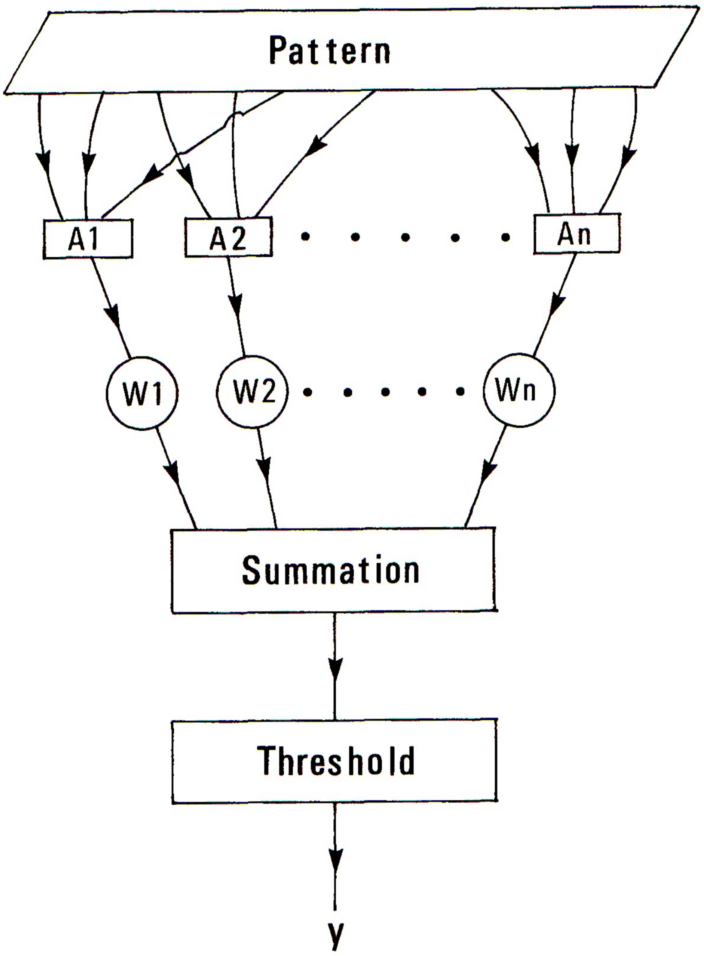

Figure 6.21: A perceptron, introduced by Rosenblatt in 1962. The perceptron is similar to a TLU, but its input is preprocessed by a set of association units (A-units). The A-units are not trained, but are assigned a fixed Boolean functionality.

Let us imagine that the input signals, $x_1, x_2, ..., x_N$ can take on the values 0 or 1. The weighted sum of the input signals will then be given by

$$a = \sum_{j=1}^{N} w_j x_j \tag{6.1}$$

The quantity a, is called the *activation.* If the activation exceeds the threshold 9, the unit "fires", i.e. it produces an output y given by

$$y = \begin{cases} 1 & \text{if} \quad a \geq \theta \\ \\ 0 & \text{if} \quad a < \theta \end{cases} \tag{6.2}$$

The decisions taken by a TLU can be given a geometrical interpretation: The input signals can be thought of as forming the components of a vector, $x = x_1, x_2, ..., X_N$, in an N-dimensional space called pattern space. The weights also form a vector, $w = w_1, w_2, ..., w_N$, in the same space. If we write an equation setting the scalar product of these two vectors equal to some constant,

$$\mathbf{w} \cdot \mathbf{x} \equiv \sum_{j=1}^{N} w_j x_j = \theta \tag{6.3}$$

then this equation defines a hyperplane in pattern space, called the *decision hyperplane.* The decision hyperplane divides pattern space into two parts - (1) input pulse patterns which will produce firing of the TLU, and (2) patterns which will not cause firing.

The position and orientation of the decision hyperplane can be changed by altering the weight vector w and/or the threshold θ. Therefore it is convenient to put the threshold and the weights on the same footing by introducing an augmented weight vector,

$$\mathbf{W} = w_1, w_2, ..., w_N, \theta \tag{6.4}$$

and an augmented input pattern vector,

$$\mathbf{X} = x_1, x_2, ..., x_N, -1 \tag{6.5}$$

In the N+l-dimensional augmented pattern space, the decision hyperplane now passes through the origin, and equation (8.3) can be rewritten in the form

$$\mathbf{W} \cdot \mathbf{X} \equiv \sum_{j=1}^{N+1} W_j X_j = 0 \tag{6.6}$$

Those input patterns for which the scalar product $\mathbf{W} \cdot \mathbf{X}$ is positive or zero will cause the unit to fire, but if the scalar product is negative, there will be no response.

If we wish to "teach" a TLU to fire when presented with a particular pattern vector $\mathbf{X}$, we can evaluate its scalar product with the current augmented weight vector $\mathbf{W}$. If this scalar product is negative, the TLU will not fire, and therefore we know that the weight vector needs to be changed. If we replace the weight vector by

$$\mathbf{W}' = \mathbf{W} + \gamma\mathbf{X} \tag{6.7}$$

where γ is a small positive number, then the new augmented weight vector $\mathbf{W}'$ will point in a direction more nearly the same as the direction of $\mathbf{X}$. This change will be a small step in the direction of making the scalar product positive, i.e. a small step in the right direction.

Why not take a large step instead of a small one? A small step is best because there may be a whole class of input patterns to which we would like the TLU to respond by firing. If we make a large change in weights to help a particular input pattern, it may undo previous learning with respect to other patterns.

It is also possible to teach a TLU to remain silent when presented with a particular input pattern vector. To do so we evaluate the augmented scalar product $\mathbf{W} \cdot \mathbf{X}$ as before, but now, when we desire silence rather than firing, we wish the scalar product to be negative, and if it is positive, we know that the weight vector must be changed. In changing the weight vector, we can again make use of equation (8.7), but now γ must be a small negative number rather than a small positive one.

Two sets of input patterns, A and B, are said to be linearly separable if they can be separated by some decision hyperplane in pattern space. Now suppose that the four sets, A, B, C, and D, can be separated by two decision hyperplanes. We can then construct a two-layer network which will identify the class of an input signal belonging to any one of the sets, as is illustrated in Figure 8.2.

The first layer consists of two TLU's. The first TLU in this layer is taught to fire if the input pattern belongs to A or B, and to be silent if the input belongs to C or D. The second TLU is taught to fire if the input pattern belongs to A or D, and to be silent if it belongs to B or C. The second layer of the network consists of four output units which are not taught, but which are assigned a fixed Boolean functionality. The first output unit fires if the signals from the first layer are given by the vector $\mathbf{y} = \{0, 0\}$ (class A); the second fires if $\mathbf{y} = \{0, 1\}$ (class B), the third if $\mathbf{y} = \{1, 0\}$ (class C), and the fourth if $\mathbf{y} = \{1, 1\}$ (class D). Thus the simple two-layer network shown in Figure 8.2 functions as a *classifier*. The output units in the second layer are analogous to the "grandmother's face cells" whose existence in the visual cortex is postulated by neurophysiologists. These cells will fire if and only if the retina is stimulated with a particular class of patterns.

This very brief glance at artificial neural networks does not do justice to the high degree of sophistication which network architecture and training algorithms have achieved during the last two decades. However, the suggestions for further reading at the end of this chapter may help to give the reader an impression of the wide range of problems to which these networks are now being applied.

Besides being useful for computations requiring pattern recognition, learning, generalization, intuition, and robustness in the face of noisy data, artificial neural networks are important because of the light which they throw on the mechanism of brain function. For example, one can compare the classifier network shown in Figure 8.2 with the discoveries of Kuffler, Hubel and Wessel concerning pattern abstraction in the mammalian retina and visual cortex.

Genetic algorithms

Genetic algorithms represent a second approach to machine learning and to computational problems involving optimization. Like neural network computation, this alternative approach has been inspired by biology, and it has also been inspired by the Darwinian concept of natural selection. In a genetic algorithm, the hardware is that of a conventional computer; but the software creates a population and allows it to evolve in a manner closely analogous to biological evolution.

One of the most important pioneers of genetic algorithms was John Henry Holland (1929-). After attending MIT, where he was influenced by Norbert Wiener, Holland worked for IBM, helping to develop the 701. He then continued his studies at the University of Michigan, obtaining the first Ph.D. in computer science ever granted in America. Between 1962 and 1965, Holland taught a graduate course at Michigan called “Theory of Adaptive Systems”. His pioneering course became almost a cult, and together with his enthusiastic students he applied the genetic algorithm approach to a great variety of computational problems. One of Holland’s students, David Goldberg, even applied a genetic algorithm program to the problem of allocating natural gas resources.

The programs developed by Holland and his students were modelled after the natural biological processes of reproduction, mutation, selection and evolution. In biology, the information passed between generations is contained in chromosomes - long strands of DNA where the genetic message is written in a four-letter language, the letters being adenine, thymine, guanine and cytosine. Analogously, in a genetic algorithm, the information is coded in a long string, but instead of a four-letter language, the code is binary: The chromosome-analogue is a long string of 0’s and 1’s, i.e., a long binary string. One starts with a population that has sufficient diversity so that natural selection can act.

The genotypes are then translated into phenotypes. In other words, the information contained in the long binary string (analogous to the genotype of each individual) corresponds to an entity, the phenotype, whose fitness for survival can be evaluated. The mapping from genotype to phenotype must be such that very small changes in the binary string will not produce radically different phenotypes. Prom the initial population, the most promising individuals are selected to be the parents of the next generation, and of these, the fittest are allowed produce the largest number of offspring. Before reproduction takes place, however, random mutations and chromosome crossing can occur. For example, in chromosome crossing, the chromosomes of two individuals are broken after the nth binary digit, and two new chromosomes are formed, one with the head of the first old chromosome and the tail of the second, and another with the head of the second and the tail of the first. This process is analogous to the biological crossings which allowed Thomas Hunt Morgan and his “fly squad” to map the positions of genes on the chromosomes of fruit flies, while the mutations are analogous to those studied by Hugo de Vries and Hermann

J. Muller.

After the new generation has been produced, the genetic algorithm advances the time parameter by a step, and the whole process is repeated: The phenotypes of the new generation are evaluated and the fittest selected to be parents of the next generation; mutation and crossings occur; and then fitness-proportional reproduction. Like neural networks, genetic algorithms are the subject of intensive research, and evolutionary computation is a rapidly growing field.

Evolutionary methods have been applied not only to software, but also to hardware. Some of the circuits designed in this way defy analysis using conventional techniques - and yet they work astonishingly well.

Artificial life

As Aristotle pointed out, it is difficult to define the precise border between life and nonlife. It is equally difficult to give a precise definition of artificial life. Of course the term means “life produced by humans rather than by nature”, but what is life? Is self-replication the only criterion? The phrase ”produced by humans” also presents difficulties. Humans have played a role in creating domestic species of animals and plants. Can cows, dogs, and high-yield wheat varieties be called “artificial life” ? In one sense, they can. These species and varieties certainly would not have existed without human intervention.

We come nearer to what most people might call “artificial life” when we take parts of existing organisms and recombine them in novel ways, using the techniques of biotechnology. For example, Steen Willadsen[10], working at the Animal Research Station, Cambridge England, was able to construct chimeras by operating under a microscope on embryos at the eight-cell stage. The zona pelucida is a transparent shell that surrounds the cells of the embryo. Willadsen was able to cut open the zona pelucida, to remove the cells inside, and to insert a cell from a sheep embryo together with one from a goat embryo. The chimeras which he made in this way were able to grow to be adults, and when examined, their cells proved to be a mosaic, some cells carrying the sheep genome while others carried the genome of a goat. By the way, Willadsen did not create his chimeras in order to produce better animals for agriculture. He was interested in the scientifically exciting problem of morphogenesis: How is the information of the genome translated into the morphology of the growing embryo?

Human genes are now routinely introduced into embryos of farm animals, such as pigs or sheep. The genes are introduced into regulatory sequences which cause expression in mammary tissues, and the adult animals produce milk containing human proteins. Many medically valuable proteins are made in this way. Examples include human blood-clotting factors, interleukin-2 (a protein which stimulates T-lymphocytes), collagen and fibrinogen (used to treat burns), human fertility hormones, human hemoglobin, and human serum albumin.

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[10] Willadsen is famous for having made the first verified and reproducible clone of a mammal. In 1984 he made two genetically identical lambs from early sheep embryo cells.

Transgenic plants and animals in which the genes of two or more species are inherited in a stable Mendelian way have become commonplace in modern laboratory environments, and, for better or for worse, they are also becoming increasingly common in the external global environment. These new species might, with some justification, be called “artificial life”.

A long period of molecular evolution probably preceded the evolution of cells. In the early 1970’s, S. Spiegelman performed a series of experiments in which he demonstrated that artificial molecular evolution can be made to take place in vitro. Spiegelman prepared a large number of test tubes in which RNA replication could take place. The aqueous solution in each of the test tubes consisted of RNA replicase, ATP, UTP (uracil triphosphate), GTP (guanine triphosphate), CTP (cytosine triphosphate) and buffer. He then introduced RNA from a bacteriophage into the first test tube. After a predetermined interval of time, during which replication took place, Spiegelman transferred a drop of solution from the first test tube to a new tube, uncontaminated with RNA. Once again, replication began and after an interval a drop was transferred to a third test tube. Spiegelman repeated this procedure several hundred times, and at the end he was able to demonstrate that the RNA in the final tube differed from the initial sample, and that it replicated faster than the initial sample. The RNA had evolved by the classical Darwinian mechanisms of mutation and natural selection. Mistakes in copying had produced mutant RNA strands which competed for the supply of energy-rich precursor molecules (ATP, UTP, GTP and CTP). The most rapidly-reproducing mutants survived. Was Spiegelman’s experiment merely a simulation of an early stage of biological evolution? Or was evolution of an extremely primitive life-form actually taking place in his test tubes?

G.F. Joyce, D.P. Bartel and others have performed experiments in which strands of RNA with specific catalytic activity (ribozymes) have been made to evolve artificially from randomly coded starting populations of RNA. In these experiments, starting populations of 1013 to 1015 randomly coded RNA molecules are tested for the desired catalytic activity, and the most successful molecules are then chosen as parents for the next generation. The selected molecules are replicated many times, but errors (mutations) sometimes occur in the replication. The new population is once again tested for catalytic activity, and the process is repeated. The fact that artificial evolution of ribozymes is possible can perhaps be interpreted as supporting the “RNA world” hypothesis, i.e. the hypothesis that RNA preceded DNA and proteins in the early history of terrestrial life.

John von Neumann speculated on the possibility of constructing artificial self-reproducing automata. In the early 1940’s, a period when there was much discussion of the Universal Turing Machine, he became interested in constructing a mathematical model of the requirements for self-reproduction. Besides the Turing machine, another source of his inspiration was the paper by Warren McCulloch and Walter Pitts entitled *A logical calculus of the ideas immanent in nervous activity*, which von Neumann read in 1943. In his first attempt (the kinematic model), he imagined an extremely large and complex automaton, floating on a lake which contained its component parts.

Von Neumann’s imaginary self-reproducing automaton consisted of four units, A, B, C and D. Unit A was a sort of factory, which gathered component parts from the surrounding lake and assembled them according to instructions which it received from other units. Unit B was a copying unit, which reproduced sets of instructions. Unit C was a control apparatus, similar to a computer. Finally D was a long string of instructions, analogous to the "tape" in the Turing machine. In von Neumann's kinematic automaton, the instructions were coded as a long binary number. The presence of what he called a "girder" at a given position corresponded to 1, while its absence corresponded to 0. In von Neumann's model, the automaton completed the assembly of its offspring by injecting its progeny with the duplicated instruction tape, thus making the new automaton both functional and fertile.

In presenting his kinematic model at the Hixton Symposium (organized by Linus Pauling in the late 1940's), von Neumann remarked that "...it is clear that the instruction [tape] is roughly effecting the function of a gene. It is also clear that the copying mechanism B performs the fundamental act of reproduction, the duplication of the genetic material, which is clearly the fundamental operation in the multiplication of living cells. It is also easy to see how arbitrary alterations of the system...can exhibit certain traits which appear in connection with mutation, lethality as a rule, but with a possibility of continuing reproduction with a modification of traits."

It is very much to von Neumann's credit that his kinematic model (which he invented several years before Crick and Watson published their DNA structure) was organized in much the same way that we now know the reproductive apparatus of a cell to be organized. Nevertheless he was dissatisfied with the model because his automaton contained too many "black boxes". There were too many parts which were supposed to have certain functions, but for which it seemed very difficult to propose detailed mechanisms by which the functions could be carried out. His kinematic model seemed very far from anything which could actually be built[11].

Von Neumann discussed these problems with his close friend, the Polish-American mathematician Stanislaw Ulam, who had for a long time been interested in the concept of self-replicating automata. When presented with the black box difficulty, Ulam suggested that the whole picture of an automaton floating on a lake containing its parts should be discarded. He proposed instead a model which later came to be known as the Cellular Automaton Model. In Ulam's model, the self-reproducing automaton lives in a very special space. For example, the space might resemble an infinite checkerboard, each square would constitute a multi-state cell. The state of each cell in a particular time interval is governed by the states of its near neighbors in the preceding time interval according to relatively simple laws. The automaton would then consist of a special configuration of cell states, and its reproduction would correspond to production of a similar configuration of cell states in a neighboring region of the cell lattice.

Von Neumann liked Ulam's idea, and he began to work in that direction. However, he

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[11] Von Neumann's kinematic automaton was taken seriously by the Mission IV Group, part of a ten-week program sponsored by NASA in 1980 to study the possible use of advanced automation and robotic devices in space exploration. The group, headed by Richard Laing, proposed plans for self-reproducing factories, designed to function on the surface of the moon or the surfaces of other planets. Like von Neumann's kinetic automaton, to which they owed much, these plans seemed very far from anything that could actually be constructed.

wished his self-replicating automaton to be able to function as a universal Turing machine, and therefore the plans which he produced were excessively complicated. In fact, von Neumann believed complexity to be a necessary requirement for self-reproduction. In his model, the cells in the lattice were able to have 29 different states, and the automaton consisted of a configuration involving hundreds of thousands of cells. Von Neumann's manuscript on the subject became longer and longer, and he did not complete it before his early death from prostate cancer in 1957. The name "cellular automaton" was coined by Arthur Burks, who edited von Neumann's posthumous papers on the theory of automata.

Arthur Burks had written a Ph.D. thesis in philosophy on the work of the nineteenth century thinker Charles Sanders Pierce, who is today considered to be one of the founders of semiotics[12]. He then studied electrical engineering at the Moore School in Philadelphia, where he participated in the construction of ENIAC, one of the first general purpose electronic digital computers, and where he also met John von Neumann. He worked with von Neumann on the construction of a new computer, and later Burks became the leader of the Logic of Computers Group at the University of Michigan. One of Burks' students at Michigan was John Holland, the pioneer of genetic algorithms. Another student of Burks, E.F. Codd, was able to design a self-replicating automaton of the von Neumann type using a cellular automaton system with only 8 states (as compared with von Neumann's 29). For many years, enthusiastic graduate students at the Michigan group continued to do important research on the relationships between information, logic, complexity and biology.

Meanwhile, in 1968, the mathematician John Horton Conway, working in England at Cambridge University, invented a simple game which greatly increased the popularity of the cellular automaton concept. Conway's game, which he called "Life", was played on an infinite checker-board-like lattice of cells, each cell having only two states, "alive" or "dead". The rules which Conway proposed are as follows: "If a cell on the checkerboard is alive, it will survive in the next time step (generation) if there are either two or three neighbors also alive. It will die of overcrowding if there are more than three live neighbors, and it will die of exposure if there are fewer than two. If a cell on the checkerboard is dead, it will remain dead in the next generation unless exactly three of its eight neighbors is alive. In that case, the cell will be 'born' in the next generation".

Originally Conway's Life game was played by himself and by his colleagues at Cambridge University's mathematics department in their common room: At first the game was played on table tops at tea time. Later it spilled over from the tables to the floor, and tea time began to extend: far into the afternoons. Finally, wishing to convert a wider audience to his game, Conway submitted it to Martin Gardner, who wrote a popular column on "Mathematical Games" for the Scientific American. In this way Life spread to MIT's Artificial Intelligence Laboratory, where it created such interest that the MIT group designed a small computer specifically dedicated to rapidly implementing Life's rules.

The reason for the excitement about Conway's Life game was that it seemed capable of generating extremely complex patterns, starting from relatively simple configurations

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[12] Semiotics is defined as the study of signs (see Appendix 2).

and using only its simple rules. Ed Fredkin, the director of MIT's Artificial Intelligence Laboratory, became enthusiastic about cellular automata because they seemed to offer a model for the way in which complex phenomena can emerge from the laws of nature, which are after all very simple. In 1982, Fredkin (who was independently wealthy because of a successful computer company which he had founded) organized a conference on cellular automata on his private island in the Caribbean. The conference is notable because one of the participants was a young mathematical genius named Stephen Wolfram, who was destined to refine the concept of cellular automata and to become one of the leading theoreticians in the field[13].

One of Wolfram's important contributions was to explore exhaustively the possibilities of 1-dimensional cellular automata. No one before him had looked at 1-dimensional CA's, but in fact they had two great advantages: The first of these advantages was simplicity, which allowed Wolfram to explore and classify the possible rule sets. Wolfram classified the rule sets into 4 categories, according to the degree of complexity which they generated. The second advantage was that the configurations of the system in successive generations could be placed under one another to form an easily-surveyed 2-dimensional visual display. Some of the patterns generated in this way were strongly similar to the patterns of pigmentation on the shells of certain molluscs. The strong resemblance seemed to suggest that Wolfram's 1-dimensional cellular automata might yield insights into the mechanism by which the pigment patterns are generated.

In general, cellular automata seemed to be promising models for gaining insight into the fascinating and highly important biological problem of morphogenesis: How does the fertilized egg translate the information on the genome into the morphology of the growing embryo, ending finally with the enormously complex morphology of a fully developed and fully differentiated multicellular animal? Our understanding of this amazing process is as yet very limited, but there is evidence that as the embryo of a multicellular animal develops, cells change their state in response to the states of neighboring cells. In the growing embryo, the "state" of a cell means the way in which it is differentiated, i.e., which genes are turned on and which off - which information on the genome is available for reading, and which segments are blocked. Neighboring cells signal to each other by means of chemical messengers[14]. Clearly there is a close analogy between the way complex patterns develop in a cellular automaton, as neighboring cells influence each other and change their states according to relatively simple rules, and the way in which the complex morphology of a multicellular animal develops in the growing embryo.

Conway's Life game attracted another very important worker to the field of cellular automata: In 1971, Christopher Langton was working as a computer programmer in the Stanley Cobb Laboratory for Psychiatric Research at Massachusetts General Hospital. When colleagues from MIT brought to the laboratory a program for executing Life, Langton was immediately interested. He recalls "It was the first hint that there was a distinction

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[13] As many readers probably know, Stephen Wolfram was also destined to become a millionaire by inventing the elegant symbol-manipulating program system, Mathematica.

[14] We can recall the case of slime mold cells which signal to each other by means of the chemical messenger, cyclic AMP.

between the hardware and the behavior which it would support... You had the feeling that there was something very deep here in this little artificial universe and its evolution through time. [At the lab] we had a lot of discussions about whether the program could be open ended - could you have a universe in which life could evolve?"

Later, at the University of Arizona, Langton read a book describing von Neumann's theoretical work on automata. He contacted Arthur Burks, von Neumann's editor, who told him that no self-replicating automaton had actually been implemented, although E.F. Codd had proposed a simplified plan with only 8 states instead of 29. Burks suggested to Langton that he should start by reading Codd's book.

When Langton studied Codd's work, he realized that part of the problem was that both von Neumann and Codd had demanded that the self-reproducing automaton should be able to function as a universal Turing machine, i.e., as a universal computer. When Langton dropped this demand (which he considered to be more related to mathematics than to biology) he was able to construct a relatively simple self-reproducing configuration in an 8-state 2-dimensional lattice of CA cells. As they reproduced themselves, Langton's loop-like cellular automata filled the lattice of cells in a manner reminiscent of a growing coral reef, with actively reproducing loops on the surface of the filled area, and "dead" (nonreproducing) loops in the center.

Langton continued to work with cellular automata as a graduate student at Arthur Burks' Logic of Computers Group at Michigan. His second important contribution to the field was an extension of Wolfram's classification of rule sets for cellular automata. Langton introduced a parameter A to characterize various sets of rules according to the type of behavior which they generated. Rule sets with a value near to the optimum ($\lambda = 0.273$) generated complexity similar to that found in biological systems. This value of Langton's λ parameter corresponded to a borderline region between periodicity and chaos.

After obtaining a Ph.D. from Burks' Michigan group, Christopher Langton moved to the Center for Nonlinear Studies at Los Alamos, New Mexico, where in 1987 he organized an "Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems" - the first conference on artificial life ever held. Among the participants were Richard Dawkins, Astrid Lindenmayer, John Holland, and Richard Laing. The noted Oxford biologist and author Richard Dawkins was interested in the field because he had written a computer program for simulating and teaching evolution. Astrid Lindenmayer and her coworkers in Holland had written programs capable of simulating the morphogenesis of plants in an astonishingly realistic way. As was mentioned above, John Holland pioneered the development of genetic algorithms, while Richard Laing was the leader of Nasals study to determine whether self-reproducing factories might be feasible.

Langton's announcement for the conference, which appeared in the Scientific American, stated that "Artificial life is the study of artificial systems that exhibit behavior characteristic of natural living systems...The ultimate goal is to extract the logical form of living systems. Microelectronic technology and genetic engineering will soon give us the capability to create new life *in silico* as well as *in vitro*. This capacity will present humanity with the most far-reaching technical, theoretical, and ethical challenges it has ever confronted. The time seems appropriate for a gathering of those involved in attempts to simulate or synthesize aspects of living systems."

In the 1987 workshop on artificial life, a set of ideas which had gradually emerged during the previous decades of work on automata and simulations of living systems became formalized and crystallized: All of the participants agreed that something more than reductionism was needed to understand the phenomenon of life. This belief was not a revival of vitalism; it was instead a conviction that the abstractions of molecular biology are not in themselves sufficient. The type of abstraction found in Darwin's theory of natural selection was felt to be nearer to what was needed. The viewpoints of thermodynamics and statistical mechanics were also helpful. What was needed, it was felt, were insights into the flow of information in complex systems; and computer simulations could give us this insight. The fact that the simulations might take place in silico did not detract from their validity. The logic and laws governing complex systems and living systems were felt to be independent of the medium.

As Langton put it, "The ultimate goal of artificial life would be to create 'life' in some other medium, ideally a virtual medium where the essence of life has been abstracted from the details of its implementation in any particular model. We would like to build models that are so lifelike that they cease to become models of life and become examples of life themselves."

Most of the participants at the first conference on artificial life had until then been working independently, not aware that many other researchers shared their viewpoint. Their conviction that the logic of a system is largely independent of the medium echoes the viewpoint of the Macy Conferences on cybernetics in the 1940's, where the logic of feedback loops and control systems was studied in a wide variety of contexts, ranging from biology and anthropology to computer systems. A similar viewpoint can also be found in biosemiotics (Appendix 2), where, in the words of the Danish biologist Jesper Hoffmeyer, "the sign, rather than the molecule" is considered to be the starting point for studying life. In other words, the essential ingredient of life is information; and information can be expressed in many ways. The medium is less important than the message.

The conferences on artificial life have been repeated each year since 1987, and European conferences devoted to the new and rapidly growing field have also been organized. Langton himself moved to the Santa Fe Institute, where he became director of the institute's artificial life program and editor of a new journal, *Artificial Life.* The first three issues of the journal have been published as a book by the MIT Press, and the book presents an excellent introduction to the field.

Among the scientists who were attracted to the artificial life conferences was the biologist Thomas Ray, a graduate of Florida State University and Harvard, and an expert in the ecology of tropical rain forests. In the late 1970's, while he was working on his Harvard Ph.D., Ray happened to have a conversation with a computer expert from the MIT Artificial Intelligence Lab, who mentioned to him that computer programs can replicate. To Ray's question "How?", the AI man answered "Oh, it's trivial."

Ray continued to study tropical ecologies, but the chance conversation from his Cambridge days stuck in his mind. By 1989 he had acquired an academic post at the University of Delaware, and by that time he had also become proficient in computer programming.

He had followed with interest the history of computer viruses. Were these malicious creations in some sense alive? Could it be possible to make self-replicating computer programs which underwent evolution by natural selection? Ray considered John Holland's genetic algorithms to be analogous to the type of selection imposed by plant and animal breeders in agriculture. He wanted to see what would happen to populations of digital organisms that found their own criteria for natural selection - not humanly imposed goals, but self-generated and open-ended criteria growing naturally out of the requirements for survival.

Although he had a grant to study tropical ecologies, Ray neglected the project and used most of his time at the computer, hoping to generate populations of computer organisms that would evolve in an open-ended and uncontrolled way. Luckily, before starting his work in earnest, Thomas Ray consulted Christopher Langton and his colleague James Farmer at the Center for Nonlinear Studies in New Mexico. Langton and Farmer realized that Ray's project could be a very dangerous one, capable of producing computer viruses or worms far more malignant and difficult to eradicate than any the world had yet seen. They advised Ray to make use of Turing's concept of a virtual computer. Digital organisms created in such a virtual computer would be unable to live outside it. Ray adopted this plan, and began to program a virtual world in which his freely evolving digital organisms could live. He later named the system "Tierra".

Ray's Tierra was not the first computer system to aim at open-ended evolution. Steen Rasmussen, working at the Danish Technical University, had previously produced a system called "VENUS" (Virtual Evolution in a Nonstochastic Universe Simulator) which simulated the very early stages of the evolution of life on earth. However, Ray's aim was not to understand the origin of life, but instead to produce digitally something analogous to the evolutionary explosion of diversity that occurred on earth at the start of the Cambrian era. He programmed an 80-byte self-reproducing digital organism which he called "Ancestor", and placed it in Tierra, his virtual Garden of Eden.

Ray had programmed a mechanism for mutation into his system, but he doubted that he would be able to achieve an evolving population with his first attempt. As it turned out, Ray never had to program another organism. His 80-byte Ancestor reproduced and populated his virtual earth, changing under the action of mutation and natural selection in a way that astonished and delighted him.

In his freely evolving virtual zoo, Ray found parasites, and even hyperparasites, but he also found instances of altruism and symbiosis. Most astonishingly of all, when he turned off the mutations in his Eden, his organisms invented sex (using mechanisms which Ray had introduced to allow for parasitism). They had never been told about sex by their creator, but they seemed to find their own way to the Tree of Knowledge.

Thomas Ray expresses the aims of his artificial life research as follows:[15] "Everything we know about life is based on one example: Life on Earth. Everything we know about intelligence is based on one example: Human intelligence. This limited experience burdens us with preconceptions, and limits our imaginations... How can we go beyond our conceptual limits, find the natural form of intelligent processes in the digital medium, and work

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[15] T. Ray, http://www.hip.atr.co.jp/ ray/pubs/pubs.html

with the medium to bring it to its full potential, rather than just imposing the world we know upon it by forcing it to run a simulation of our physics, chemistry and biology?..."

"In the carbon medium it was evolution that explored the possibilities inherent in the medium, and created the human mind. Evolution listens to the medium it is embedded in. It has the advantage of being mindless, and therefore devoid of preconceptions, and not limited by imagination." "I propose the creation of a digital nature - a system of wildlife reserves in cyberspace in the interstices between human colonizations, feeding off unused CPU-cycles and permitted a share of our bandwidth. This would be a place where evolution can spontaneously generate complex information processes, free from the demands of human engineers and market analysts telling it what the target applications are - a place for a digital Cambrian explosion of diversity and complexity..."

"It is possible that out of this digital nature, there might emerge a digital intelligence, truly rooted in the nature of the medium, rather than brutishly copied from organic nature. It would be a fundamentally alien intelligence, but one that would complement rather than duplicate our talents and abilities."

Have Thomas Ray and other "a-lifers"[16] created artificial living organisms? Or have they only produced simulations that mimic certain aspects of life? Obviously the answer to this question depends on the definition of life, and there is no commonly agreed-upon definition. Does life have to involve carbon chemistry? The a-lifers call such an assertion "carbon chauvinism". They point out that elsewhere in the universe there may exist forms of life based on other media, and their program is to find medium-independent characteristics which all forms of life must have.

A living organism is a complex system produced by an input of thermodynamic information in the form of Gibbs free energy. This incoming information keeps the system very far away from thermodynamic equilibrium, and allows it to achieve a statistically unlikely and complex configuration. The information content of any complex (living) system is a measure of how unlikely it would be to arise by chance. With the passage of time, the entropy of the universe increases, and the almost unimaginably improbable initial configuration of the universe is converted into complex free-energy-using systems that could never have arisen by pure chance. Life maintains itself and evolves by feeding on Gibbs free energy, that is to say, by feeding on the enormous improbability of the initial conditions of the universe.

All of the forms of artificial life that we have discussed derive their complexity from the consumption of free energy. For example, Spiegelman's evolving RNA molecules feed on the Gibbs free energy of the phosphate bonds of their precursors, ATP, GTP, UTP, and CTP. This free energy is the driving force behind artificial evolution which Spiegelman observed. In his experiment, thermodynamic information in the form of high-energy phosphate bonds is converted into cybernetic information.

Similarly, in the polymerase chain reaction, the Gibbs free energy of the phosphate bonds in the precursor molecules ATP, TTP, GTP and CTP drives the reaction. With the aid of the enzyme DNA polymerase, the soup of precursors is converted into a highly

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[16] In this terminology, ordinary biologists are "b-lifers".

improbable configuration consisting of identical copies of the original sequence. Despite the high improbability of the resulting configuration, the entropy of the universe has increased in the copying process. The improbability of the set of copies is less than the improbability of the high energy phosphate bonds of the precursors.

The polymerase chain reaction reflects on a small scale, what happens on a much larger scale in all living organisms. Their complexity is such that they never could have originated by chance, but although their improbability is extremely great, it is less than the still greater improbability of the configurations of matter and energy from which they arose. As complex systems are produced, the entropy of the universe continually increases, i.e., the universe moves from a less probable configuration to a more probable one.

In Thomas Ray's experiments, the source of thermodynamic information is the electrical power needed to run the computer. In an important sense one might say that the digital organisms in Ray's Tierra system are living. This type of experimentation is in its infancy, but since it combines the great power of computers with the even greater power of natural selection, it is hard to see where it might end.

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Chapter 7

THE MECHANISM OF CELL DIFFERENTIATION

7.1 Embryonic stem cells

An embryonic stem cell is like a child at birth. The child's destiny is not yet determined. All possibilities are open. As the child grows to be an adolescent and later an adult, his or her identity becomes gradually more and more closely defined. Choices and events begin to restrict the range of possibilities, and the person's identity becomes more and more clear. In a closely analogous way, in the growing embryo, the cell's identity becomes progressively more and more closely defined. In both the case of the person and that of the cell, we can recognize the operation of decision trees, like those of Linnaeus, or those of grammatical classification in languages.

Figure 7.1 shows the development of an embryo from morula to blastula. At the blastula stage, the stem cells are all equal, all undifferentiated. In Figure 7.2, however, a section of the surface of the blastula folds inwards, and a gastrula is formed. Now the cells are not all equal. Those on the outside form the ectoderm, while those on the inside have become the endoderm (meaning "inside the skin"). The cells in each group now are partially differentiated. They have different destinies. Because of their different positions, they are exposed to different chemical environments. This process is repeated again and again during the growth of the embryo. The number of environments proliferates, and the identities of the cells become progressively more and more closely defined.

Diseases and conditions where stem cell treatment is being investigated

- Diabetes
- Androgenic Alopecia and hair loss
- Rheumatoid arthritis
- Parkinson's disease

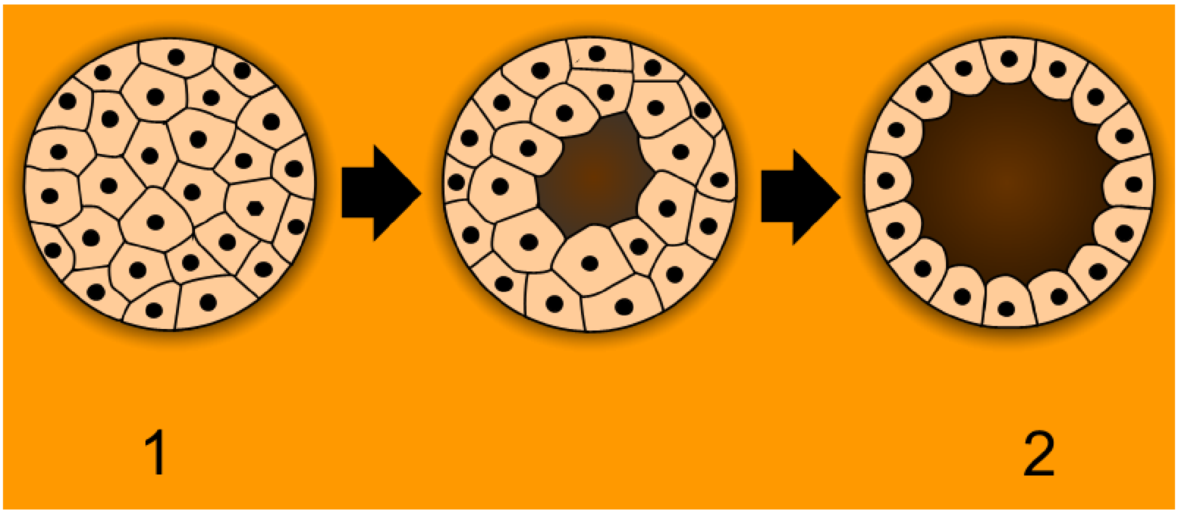

Figure 7.1: **1 - morula, 2 - blastula.**

- Alzheimer's disease
- Osteoarthritis
- Stroke and traumatic brain injury repair
- Learning disability due to congenital disorder
- Spinal cord injury repair
- Heart infarction
- Anti-cancer treatments
- Baldness reversal
- Replace missing teeth
- Repair hearing
- Restore vision and repair damage to the cornea
- Amyotrophic lateral sclerosis
- Crohn's disease
- Wound healing
- Male infertility due to absence of spermatogonial stem cells. In recent studies, scientist have found a way to solve this problem by reprogramming a cell and turning it into a spermatozoon. Other studies have proven the restoration of spermatogenesis by introducing human iPSC cells in mice testicles. This could mean the end of azoospermia.
- Female infertility: oocytes made from embryonic stem cells. Scientists have found the ovarian stem cells, a rare type of cells (0.014%) found in the ovary. They could be used as a treatment not only for infertility, but also for premature ovarian insufficiency.

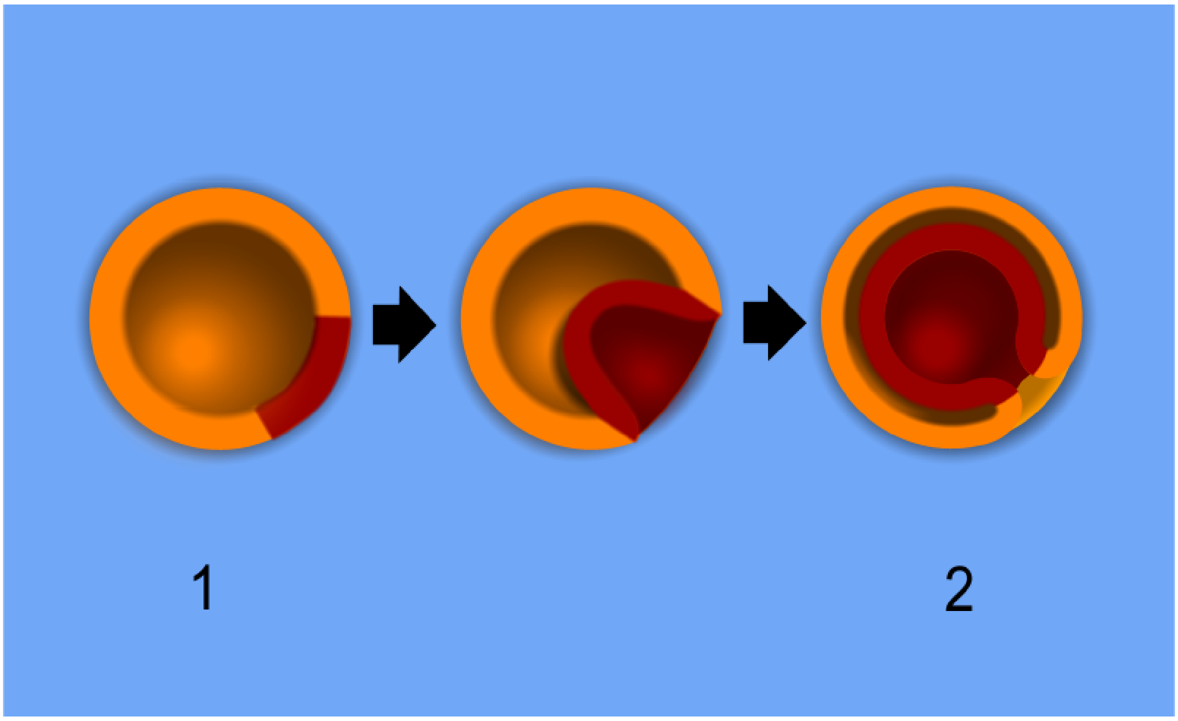

Figure 7.2: **1 - blastula, 2 - gastrula with blastopore; orange - ectoderm, red - endoderm.**

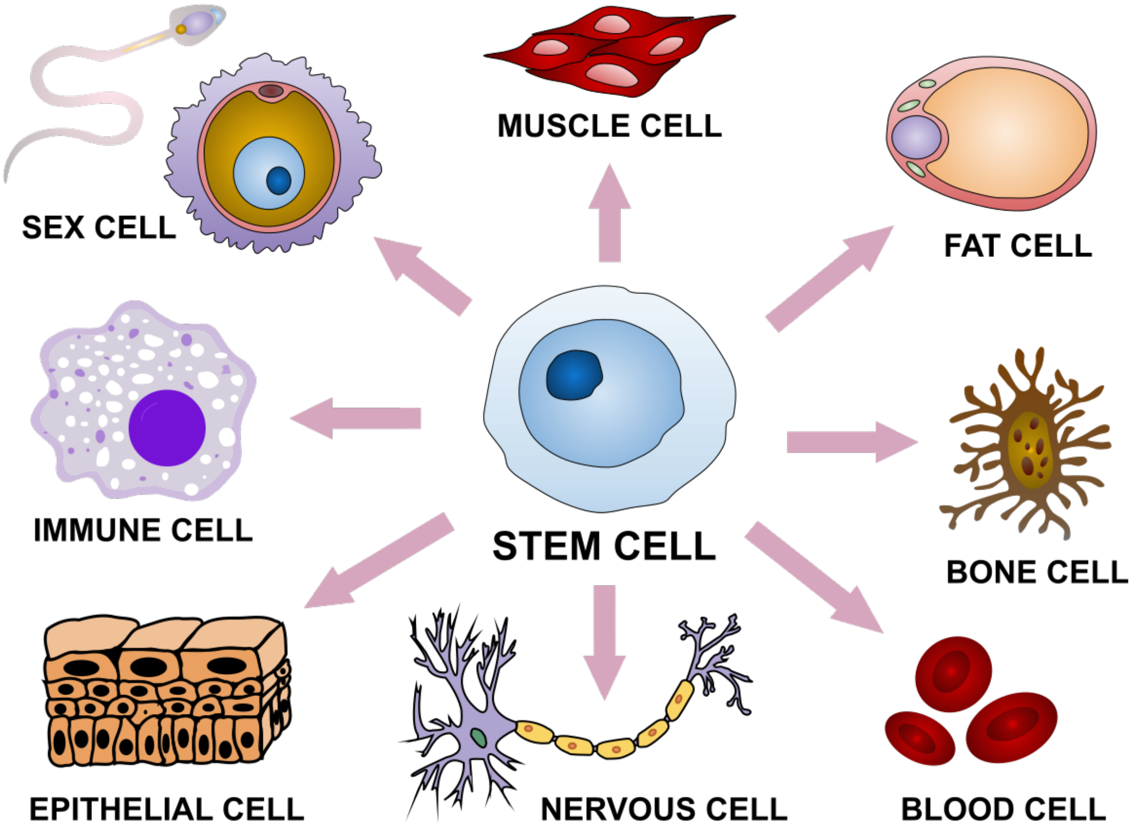

Figure 7.3: **Stem cell differentiation into various tissue types.**

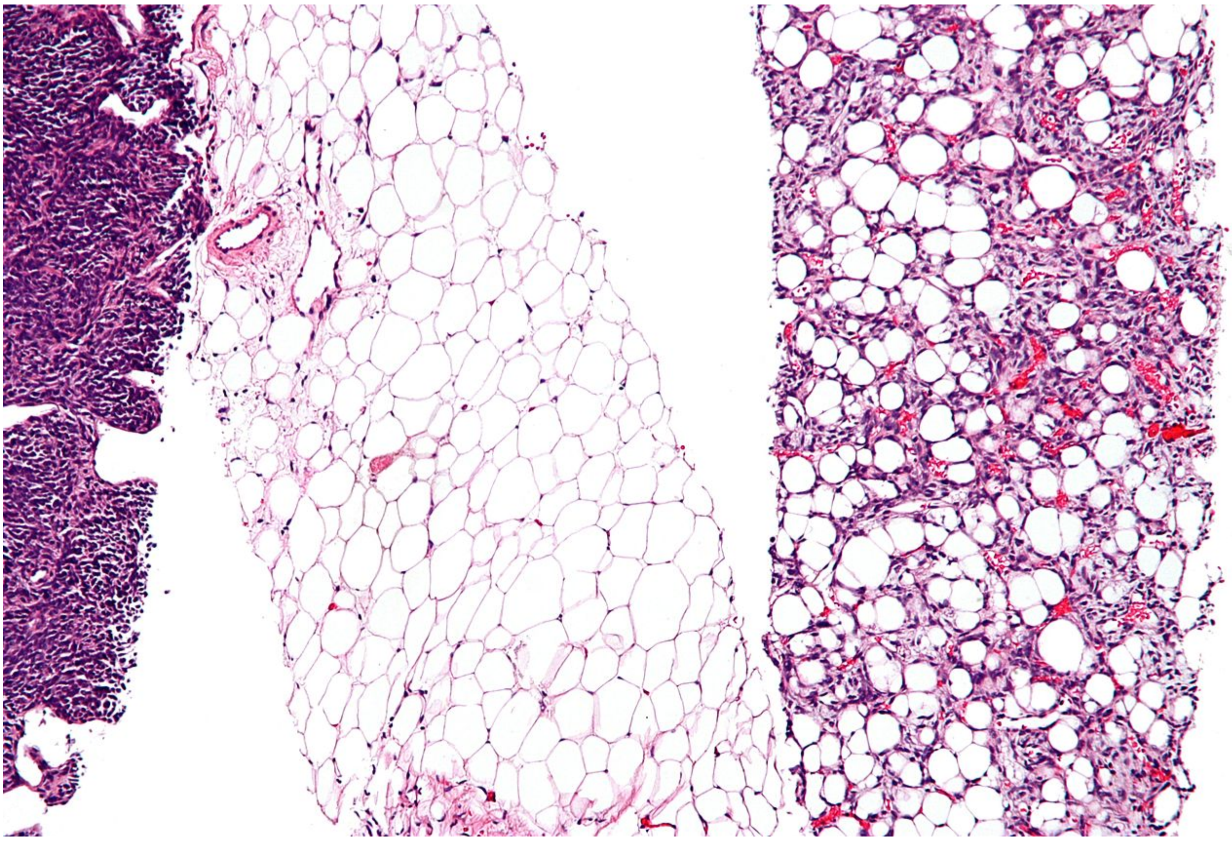

Figure 7.4: **Micrograph of a liposarcoma with some dedifferentiation, that is not identifiable as a liposarcoma, (left edge of image) and a differentiated component (with lipoblasts and increased vascularity (right of image)). Fully differentiated (morphologically benign) adipose tissue (center of the image) has few blood vessels. H&E stain.**

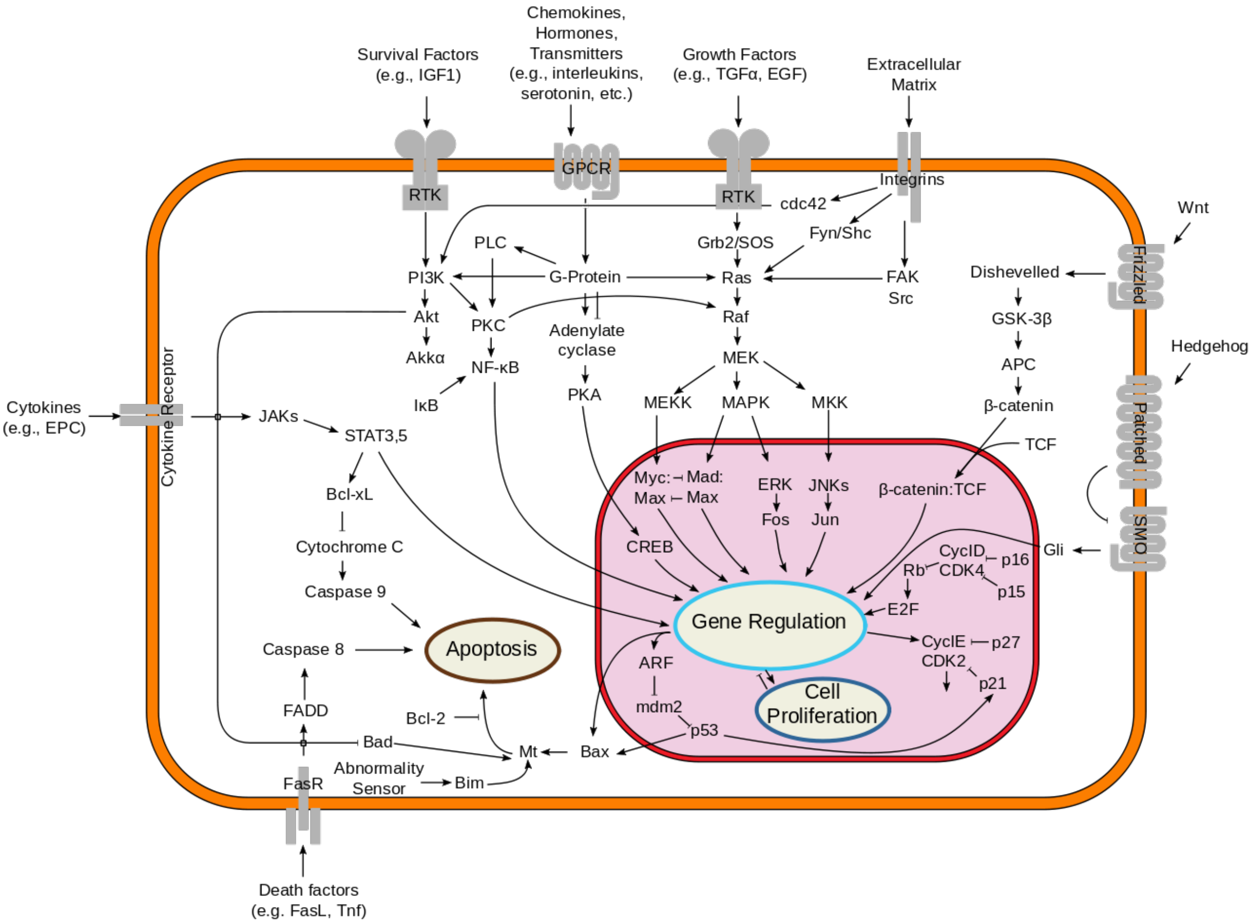

Figure 7.5: **An overview of major signal transduction pathways.**

7.2 Insect juvenile hormones and chromosomal puffs

During the summer of 1960, when I was working at the Marine Biological Laboratory at Woods Hole Massachusetts, [1] I heard a wonderful lecture by Professor Carroll Williams of Harvard University. He had done an ingenious series of experiments which demonstrated the mechanism of insect juvenile hormones. These hormones mediate the process of metamorphosis in insects such as caterpillars, which undergo Metamorphosis and become butterflys or moths.

As long as the juvenile hormone is present, holometabalos Metamorphosis does not take place. If we continue to dose a caterpillar with the appropriate juvenile hormone, it will just continue to grow larger, and will never turn into a butterfly. Williams wondered: What is the mechanism? He began working with a species of butterfly that had very large chromosomes, easily visible under the microscope. Normally, prior to Metamorphosis, large puffs formed on the chromosomes. Williams deduced that the function of these puffs is to make the base sequences of the DNA, normally tightly bound within the chromosome, available for reading and RNA transcription. He then labeled the juvenile hormones, which were chemically identified as histones, with radioactive tracers, and allowed them to act on the chromosomes. By making radioautographs, he found the the histones were binding to the places on the chromosomes where puffs would normally form during Metamorphosis. The the mechanism was clear. The histones were preventing the reading of the genetic information needed to make the transition from larva to adult.

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[1] in the laboratory of the great biochemist and physiologist Albert Szent-Györgyi

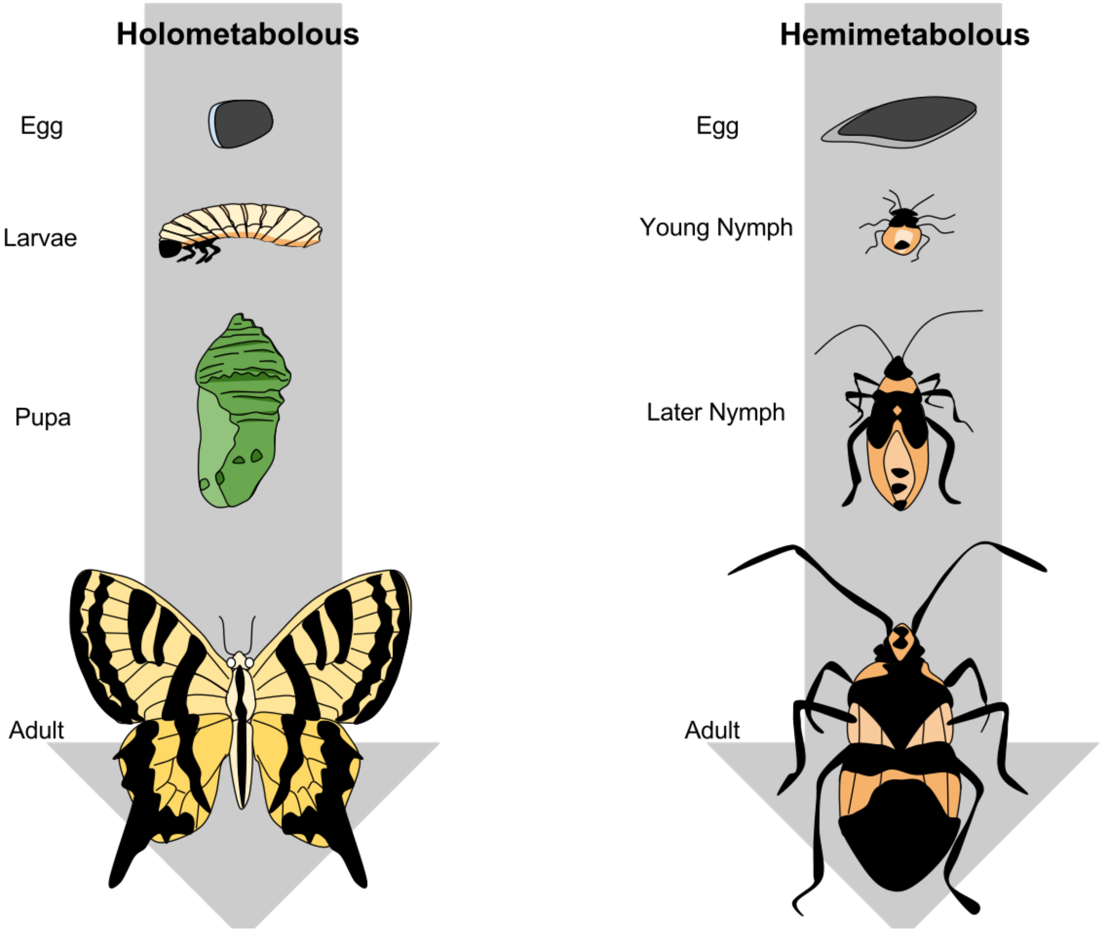

Figure 7.6: **Two types of metamorphosis are shown. In a complete (holometabolous) metamorphosis the insect passes through four distinct phases, which produce an adult that does not resemble the larva. In an incomplete (hemimetabolous) metamorphosis an insect does not go through a full transformation, but instead transitions from a nymph to an adult by molting its exoskeleton as it grows.**

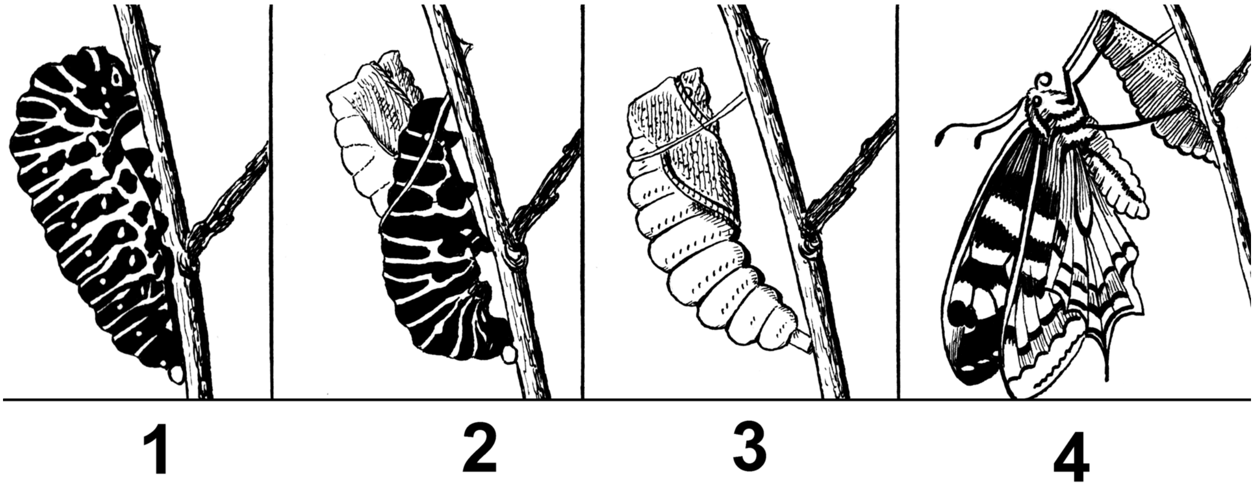

Figure 7.7: **Metamorphosis of a butterfly.**

Figure 7.8: **Almost functional common frog with some remains of the gill sac and a not fully developed jaw.**

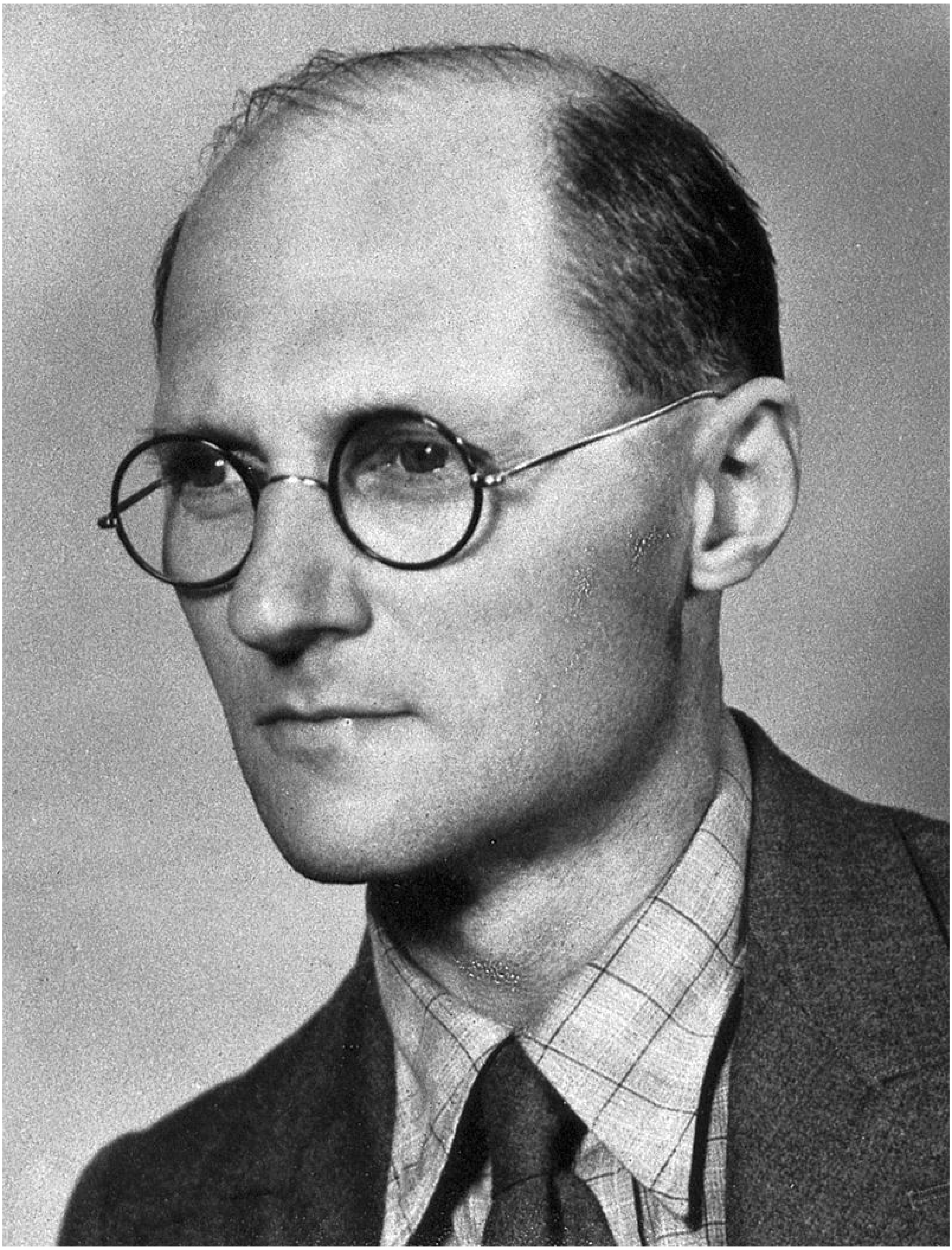

Figure 7.9: **Sir Vincent Brian Wigglesworth (1899-1994). His most significant contribution to entomology was the discovery that neurosecretory cells in the brain of the South American kissing bug, Rhodnius prolixus, secrete a crucial hormone that triggers the prothoracic gland to release prothoracicotropic hormone (PTTH), which regulates the process of metamorphosis.**

Figure 7.10: **Noted entomologist Carroll Williams, shown here at the Xth International Congress of Entomology in August 1956 (Montreal, Quebec, Canada).**

7.3 Evan Balaban: The new Frankenstein

I hope that the reader will not be offended if I introduce a personal memory at this point: During the 1990's I was on a working visit to the laboratory of the famous chemical physicist Dudley R. Herschbach at Harvard University. At a Harvard party, a gentleman introduced himself to me with the words, "I am Balaban. I am the new Frankenstein.".

As I talked with Professor Evan Balaban, who normally worked at McGill University, I began to understand what he meant by that. He had performed experiments in which he operated on chick embryos from various species of birds. In these experiments, he transplanted the tissues that normally would develop into the brain and nervous system of one species into a different species, after removing the corresponding part from the host embryo. He then carefully sealed the hole in the egg through which he had operated, and waited for the chick to hatch and grow to adulthood. He was interested to know whether the songs of the adult bird would be those of the host species of the donor species. I waited excitedly for his answer. He said that the results were mixed. The songs were sometimes those of the donor species, and sometimes those of the host.

He was not doing these experiments in order to create monsters, like Mary Shelly's original Dr. Frankenstein, but rather to throw light on the mechanism of cell differentiation. To what extent is a cell's destiny produced by its own genome, and to what extent by chemical influences from the surrounding tissues? I believe that Prof. Balaban has initiated an interesting line of research that ought to be explored further.

Here are some excerpts from an article by Jack Lucentini entitled *Brain Swapping Comes Of Age*[2]:

> **"For more than two decades, Evan Balaban has honed his skills at manipulating embryonic tissue samples using tiny instruments of his own making. He can cut a small access window into a quail's egg, and using a scalpel no wider than a human hair, excise a few hundred thousand cells from the bird's developing central nervous system. This is only the first step of the intricate process required to place this minuscule brain into another animal's head. Some of these surgeries end in untimely death for brain-transplanted embryos, but Balaban says he has elevated the typical survival rate from less than 20% to more than 60%. That was unimaginable in the 1950s, he says, when success was more along the lines of one or two in 1,000, and some researchers 'were doing this with piano wire.'**
>
> **"But don't cue the maniacal laughter just yet. As much T.H. Morgan as it is Dr. Moreau, brain-swapping research is coming into its own, with the potential to answer questions other technologies can't, says Balaban. This associate professor of behavioral neuroscience at McGill University in Montreal is unfazed by the contrast between the glitz of kindred work, such as stem cell implantation, and the whiff of gothic horror that accompanies his work.**

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[2] https://www.the-scientist.com/notebook-old/brain-swapping-comes-of-age-47771

"Far from being a throwback, he insists, brain swapping is 'really working at the right level for answering a lot of interesting questions about brain development and behavior,' and techniques are improving all the time. Not until two or three decades ago did biologists understand brain circuitry well enough to make good scientific use of brain transplants, though they have been technically feasible since H.G. Wells' time. Since then, researchers have swapped the brains of various species of frogs and salamanders, as well as ducks, in addition to the quails and chicks that Balaban uses. He plans on trying it on songbirds too."

7.4 Chemical messengers in cell differentiation

My brother, Professor Gordon B. Avery (born in 1931), obtained both his M.D. degree and his Ph.D. degrees simultaneously at the University of Pennsylvania. He was the first student ever to do so. His Ph.D. thesis, performed under the supervision of Professor Howard Holtzer is particularly interesting because of the light which it throws on the mechanism of cell differentiation.

Professor Holtzer had been especially interested in the role of the spinal cord in differentiating the cells around it during the development of the embryo. As both Ernst Haeckel and Charles Darwin noticed, the development of embryos seems to repeat the stages in the evolution of species. In Haeckel's words, "Ontogeny recapitulates phylogeny".

Since the difference between vertebrates and non-vertebrates is such an important one in evolution, Holtzer focused his research on the embryological role of the spinal cord. Gordon's Ph.D. research in Holtzer's laboratory involved, among other things, operating under a microscope on 3-day-old chicken embryos to remove the notocord. He took undifferentiated cells from the embryos and cultured both the cells and the notocord on opposite sides of a piece of filter paper. But still the notocord was able to differentiate the cells on to opposite side of the paper, although there could be no physical contact between them. This proved that a chemical substance was involved in the differentiation, since the substance could pass right through the filter paper.

Perhaps one day someone will complete Gordon's pioneering work by isolating the chemical substance by which the notocord differentiates neighboring cells in a growing embryo. In fact, what Gordon's experiments uncovered may be a much more general principle, and it may be the general rule that differentiation is accomplished through the agency of chemical transmitter substances.

Suggestions for further reading

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