

THE LIBRARY OF CONGRESS

Dewey Section

To: Caroline Kent, Chair
Decimal Classification Editorial Policy Committee

Cc: Members of the Decimal Classification Editorial Policy Committee
Karl E. Debus-López, Chief, U.S. General Division

From: Rebecca Green, Assistant Editor
Dewey Decimal Classification
OCLC Online Computer Library Center, Inc.

Via: Michael Panzer, Editor in Chief
Dewey Decimal Classification
OCLC Online Computer Library Center, Inc

Re: Natural computing

Expansions

006.38	Natural computing
006.382	Nature-inspired models and techniques of computation
006.382 2	Cellular automata
006.382 3	Neural computation
006.382 4	Evolutionary computation
006.382 5	Swarm intelligence
006.382 6	Artificial immune systems and artificial life
006.382 62	Artificial immune systems
006.382 64	Artificial life
006.384	Computing with natural materials
006.384 2	Molecular computing
006.384 3	Quantum computing

EPC Exhibit 136-12.1 mentioned that some of the current computer science topics needing accommodation in the DDC were being treated in other exhibits. This is one of those exhibits. Natural computing topics have been on our radar screen for a while now— we mapped several LCSH for natural computing topics to 006.3 Artificial intelligence three years ago—but we have not had the opportunity to address natural computing as a whole until now.

Because of the breadth of the field, we considered it important to get feedback from subject matter experts. We identified and then contacted three persons with apparent expertise across the field; we heard back from two of them who had, on their own, joined efforts to respond to our inquiry:

Dr. Grzegorz Rozenberg (rozenber@liacs.nl)

- Director of the Leiden Center for Natural Computing
- Editor-in-chief of the International Journal on Natural Computing (Kluwer Academic Publishers)
- Editor-in-chief of Theoretical Computer Science C: Theory of Natural Computing (Elsevier)
- Editor-in-chief of the Natural Computing Book Series (Springer-Verlag)
- The person who first coined the phrase “natural computing” (some 25 years ago)

Dr. Lila Kari (lila@csd.uwo.ca)

- Professor, Department of Computer Science, University of Western Ontario
- Area Editor for molecular computing for Natural Computing (Springer Verlag)
- Member of the Editorial Board of Theoretical Computer Science, Natural Computing Series (Springer Verlag)

Drs. Kari and Rozenberg co-authored an invited review article entitled “The Many Facets of Natural Computing,” which appeared in *Communications of the ACM*, 51/10 (October 2008): 72-83. This article presents the following overview of natural computing:

Natural computing is the field of research that investigates models and computational techniques inspired by nature and, dually, attempts to understand the world around us in terms of information processing. It is a highly interdisciplinary field that connects the natural sciences with computing science, both at the level of information technology and at the level of fundamental research.

They provided us the following outline of natural computing, which mirrors the structure of the review article (brief characterizations of each topic, drawn from the review article or from the closely aligned Wikipedia article on “Natural computing”, are found in the appendix):

1. Nature as Inspiration
 - a. Cellular Automata
 - b. Neural Computation (neural networks)
 - c. Evolutionary Computation (genetic algorithms, genetic programming)
 - d. Swarm Intelligence (particle swarm optimization, ant algorithms)
 - e. Artificial Immune Systems
 - f. Artificial Life (Lindenmayer systems, mechanical artificial life, artificial chemistry)
 - g. Membrane Computing
 - h. Amorphous Computing
2. Nature as Implementation Substrate
 - a. Molecular (DNA) Computing
 - b. Quantum Computing
3. Nature as Computation
 - a. Systems Biology (Computational systems biology, gene regulatory networks, biochemical networks, transport networks)
 - b. Synthetic Biology (artificial organisms, cell-to-cell communication)
 - c. Cellular Computing (in vivo computing)

Most of these topics have corresponding LCSH and enjoy substantial literary warrant:

LCSH	Outline match	WorldCat count	Corresponding LCC class / LCSH BTs / notes on DDC classification in WorldCat
Ant algorithms	1d	127	BTs: Algorithms; Mathematical optimization
Biocomputers	2a	79	LCC: QA76.884 BT: Computers
Biologically-inspired computing	1	379	BTs: Bionics; Electronic data processing
Cellular automata	1a	2681	LCC: QA267.5.C45 BTs: Parallel processing (Electronic computers) ; Pattern recognition systems; Sequential machine theory
Evolutionary computation	1c	2127	BT: Neural networks (Computer science)
Evolutionary programming (Computer science)	1c	1475	LCC: QA76.618 BT: Computer programming
Gene regulatory networks	3a	232	BTs: Genetic regulation; Nucleotide sequence DDC notes: most literature in 570s
Genetic algorithms	1c	5904	BTs: Algorithms; Combinatorial optimization; Evolutionary computation
Genetic programming (Computer science)	1c	699	LCC: QA76.623 BT: Computer programming
Immunocomputers	1e	95	LCC: QA76.875 BTs: Biologically-inspired computing; Electronic digital computers
L systems	1f	199	LCC: QH491 BTs: Developmental biology -- Mathematical models; Formal languages; Machine theory
Molecular computers	2a	500	LCC: QA76.887 BTs: Biocomputers; Biologically-inspired computing
Natural computation	All	166	LCC: QA76.9.N37 BT: Electronic data processing
Neural computers	1b	1781	LCC: QA76.87 BT: Electronic digital computers
Neural networks (Computer science)	1b	15874	LCC: QA76.87 BTs: Artificial intelligence; Biologically-inspired computing; Soft computing
Quantum computers	2b	1756	LCC: QA76.889
Swarm intelligence	1d	858	LCC: Q337.3 BTs: Cellular automata; Distributed artificial intelligence

LCSH	Outline match	WorldCat count	Corresponding LCC class / LCSH BTs / notes on DDC classification in WorldCat
Synthetic biology	3b	525	BTs: Biology; Engineering DDC notes: if given DDC number, mostly in 500s and 600s
Systems biology	3a	2418	BT: Computational biology DDC notes: if given DDC number, mostly in 500s and 600s

The LCSH data raise several issues needing consideration. They include:

1. How natural computing is organized in *Association for Computing Machinery (ACM) Computing Classification System, 2012 Revision*

The outline below shows the basic organizational structure in which natural computing topics fit in the current ACM Computing Classification. Two observations can be made. (1) We note that some of the topics are not fully fitted into the structure, given their subordination to classes such as Emerging technologies and Other architectures. Other topics are part of fully organized hierarchies. But the placement of neural networks within machine learning predates natural computing. And natural computing topics within the Applied computing / Life and medical sciences / Computational biology hierarchy are governed more by the organization of the life sciences than that of computer science. (See discussion of issue 5 below.) (2) The distribution of natural computing topics across disparate top-level groups—hardware, computer system organization, computing methodologies, applied computing—implies not having a single natural computing development. (See discussion of issue 6 below.)

Hardware

- Emerging technologies
 - Biology-related information processing
 - Neural systems
- Circuit substrates
 - Cellular neural networks
- Quantum technologies
 - Quantum computation
 - Quantum dots and cellular automata

Computer systems organization

- Architectures
 - [Serial architectures]
 - [Parallel architectures]
 - [Distributed architectures]
- Other architectures
 - Neural networks
 - Quantum computing
 - Molecular computing

Computing methodologies
 Machine learning
 Machine learning approaches
 Neural networks

Applied computing
 Life and medical sciences
 Computational biology
 Genomics
 Computational genomics
 Systems biology

2. Other classificatory structures for natural computing

How widely accepted is the overall conceptual structure proposed by Kari and Rozenberg? In looking at top-level breakdowns of natural computing in various contexts, we find the field split in different, but remarkably compatible, ways. The IJNCR mission statement and TPNC aims statement include an additional category: “methods to computationally synthesize natural phenomena” = “synthesis of nature by means of computation.” The specific topics included here within that category are artificial chemistry, artificial immune systems, and artificial life, which the Kari-Rozenberg outline treats as two subcategories of its nature-as-inspiration category. (However, the Wikipedia article on “Natural Computing” includes a section on “Synthesizing nature by means of computing,” which includes artificial life, while artificial immune systems are part of the section on “Nature-inspired models of computation.”) The Kari-Rozenberg outline appears to provide a satisfactory basis for a natural computing development in the DDC.

Kari and Rozenberg, “The Many Facets of Natural Computing” CACM article	<i>International Journal of Natural Computing Research</i> (IJNCR) mission statement; Leandro Nunes de Castro, editor	1st International Conference on the Theory and Practice of Natural Computing (TPNC); topics in call for papers / aims	<i>Natural Computing: An International Journal</i> aims and scope statement; Editors-in-Chief: G. Rozenberg; H.P. Spaink
nature as inspiration	nature-inspired computing	nature-inspired models of computation	computing inspired by nature
	methods to computationally synthesize natural phenomena	synthesis of nature by means of computation	
nature as implementation substrate	novel computing paradigms based on natural materials	nature-inspired materials	
nature as computation		information processing in nature	computing going on in nature

3. Topics without LCSH

The following topics from the Kari-Rozenberg natural computing outline do not have corresponding LCSHs: membrane computing, amorphous computing, and cellular computing / in vivo computing. A keyword phrase search on “membrane computing” retrieves only 1 record in WorldCat. A keyword phrase search on “amorphous computing” retrieves 52 records in WorldCat; restricting the phrase search to subject fields retrieves 14 records and to title fields 10 records. A keyword phrase search on “cellular computing” retrieves 50 records in WorldCat; restricting the phrase search to subject fields retrieves 6 records and to title fields 32 records (13 titles) (expanding the searches with “in vivo computing” retrieves no additional records). The literary warrant for membrane computing does not justify further consideration at this time. The literary warrant for amorphous computing and for cellular computing justify mention in a class description and being indexed, but do not justify expansion.

4. Conceptual structure implied by LCSH BTs

Only a few relationships between natural computing topics are captured within the LCSH data:

- Evolutionary computation
 - BT Neural networks (Computer science)
- Genetic algorithms
 - BT Evolutionary computation
- Immunocomputers
 - BT Biologically-inspired computing
- Molecular computers
 - BT Biocomputers
 - Biologically-inspired computing
- Neural networks (Computer science)
 - BT Biologically-inspired computing
- Swarm intelligence
 - BT Cellular automata

Several of the relationships (Evolutionary computation BT Neural networks; Molecular computers BT Biologically-inspired computing; and Swarm intelligence BT Cellular automata) do not reflect the conceptual structure of the Kari-Rozenberg outline. On the one hand, their review article indicates: “A few words are in order about the organization of this article. The classifications and labels we use for various fields of research are purely for the purpose of organizing the discourse. In reality, far from being clear-cut, many of the fields of research mentioned here overlap, or fit under more than one category.” Nevertheless, I am unable to establish conventional relationships between evolutionary computation and neural networks or between swarm intelligence and cellular automata. Furthermore, the relationship between Molecular computers and Biologically-inspired computing was probably established in 2005, when these two headings were established, which is several years before the heading Natural computation was established. In short, it does not appear that the hierarchical relationships between these LCSHs add anything new that we need to take into account.

5. Split between computer science and natural sciences

The LCC and DDC class numbers correlated with the natural computing LCSHs, as well as the hierarchical relationships given for the LCSHs, place most of the topics in the realm of computer science; some of the topics, however, appear to fit better in the natural sciences:

Computer science topics

- Ant algorithms
- Biocomputers
- Biologically-inspired computing
- Cellular automata
- Evolutionary computation
- Evolutionary programming (Computer science)
- Genetic algorithms
- Genetic programming (Computer science)
- Immunocomputers
- Molecular computers
- Natural computation
- Neural computers
- Neural networks (Computer science)
- Quantum computers
- Swarm intelligence (BT: Cellular automata, but also LCC: Q337.3)

Natural science topics

- Gene regulatory networks
- L systems
- Synthetic biology
- Systems biology

The general pattern is that topics from the Nature-as-Inspiration and Nature-as-Implementation-Substrate parts of the outline belong in computer science, while topics from the Nature-as-Computation part of the outline belong in the natural sciences. These latter topics might be best treated as computer applications. This is sensible in that topics in the Nature-as-Computation part of the outline view natural phenomena as information processing.

6. Where to locate natural computing development

As just shown, most of our natural computing topics should probably find their home within computer science. If we were to follow the ACM Classification model, we might distribute these topics among hardware, architecture, and other types of numbers. But users are likely to expect an intact natural computing development; Drs. Kari and Rozenberg explicitly rejected the possibility of classing Nature-as-Implementation-Substrate topics in an 004 number.

A natural computing development would have to find its home somewhere in 006 Special computer methods. Three possible neighborhoods emerge:

- An expansion under 006.2 Special-purpose systems

- An expansion within 006.3 (at 006.38 or 006.39, with 006.3 becoming Artificial intelligence and natural computing)
- An expansion at 006.9

None of the three options is ideal:

- Natural computing isn't a special-purpose system (which is unfortunate, since 006.2 has more room for expansion than elsewhere).
- Natural computing is not a subclass of artificial intelligence, although there are some affinities. Creating an expansion under 006.3 would require recasting the scope of 006.3, which has a well-defined scope at present. (A similar strategy could be executed under 006.2 but Special-purpose systems and natural computing make for an odd couple.)
- Creating an expansion on notation 9 is generally considered a last-resort option.

Of these options, using 006.38 might be considered the least worst. Not only does it avoid the worst of the problems cited above, but it also has the advantage of the most natural accommodation for moving topics now mapped to 006.3 to a new home.

The proposed new development is presented on the next two pages. Several existing classes are also shown, with needed changes **highlighted**.

.1 *Programming

Class here application frameworks, application programming, computer algorithms, integrated development environments, software engineering

Class algorithms discussed solely from a theoretical perspective, without regard to computer implementation, in 518.1. Class a specific application of programming within computer science with the application in 005.4–005.8 or 006, e.g., **evolutionary programming 006.3824**, programming of computer graphics 006.66

For programming for specific types of computers, for specific operating systems, for specific user interfaces, see 005.2

See Manual at 005.1–005.2 vs. 005.42; also at 005.1 vs. 005.3

.3 *Artificial intelligence and natural computing

Standard subdivisions are added for artificial intelligence and natural computing together, for artificial intelligence alone

Class here computational intelligence, intelligent agents, multi-agent systems, question-answering systems, comprehensive works on artificial intelligence and cognitive science

Class **swarm intelligence in 006.3825**; class robotics in 629.892

For cognitive science, see 153

See also 005.115 for logic programming; also 006.4 for pattern recognition not used as a tool of artificial intelligence

See Manual at 006.3 vs. 153

.31 *Machine learning

For machine learning in knowledge-based systems, see 006.331

Genetic algorithms, genetic programming relocated to 006.3824

.32 *Neural nets (Neural networks)

Including perceptrons

Class here connectionism, neural computers

For neural computations, neural networks in natural computing, see 006.3823

.38 *Natural computing

For information processing in nature, see 570.285

.382 *Nature-inspired models and techniques of computation

Standard subdivisions are added for either or both topics in heading

Including amorphous computing

Class here biologically-inspired computing

For computing with natural materials, see 006.384

*Use notation 019 from Table 1 as modified at 004.019

- .382 2 *Cellular automata
- .382 3 *Neural computation
 Class here neural networks
 Class comprehensive works on neural networks in 006.32
- .382 4 *Evolutionary computation
 Class here genetic algorithms, genetic programming [*both formerly*
 006.31], evolutionary programming
- .382 5 *Swarm intelligence
 Including ant algorithms, particle swarm optimization
- .382 6 *Artificial immune systems and artificial life
- .382 62 *Artificial immune systems
 Class here immunocomputing
- .382 64 *Artificial life
- .384 *Computing with natural materials
- .384 2 *Molecular computing
 Variant names: biomolecular computing, biocomputing
 Class here biochemical computing, DNA computing
- .384 3 *Quantum computing
- .285 Computer applications
 Class here information processing in nature
 For a specific natural phenomenon as information processing, see
 the phenomenon, plus notation 0285 from Table 1, e.g., cellular
 computing as information processing 571.60285, gene regulatory
 networks as information processing 572.8650285

*Use notation 019 from Table 1 as modified at 004.019

Appendix

(characterizations drawn from Kari-Rozenberg review article
or Wikipedia article on “Natural computing”)

1. Nature as Inspiration / Nature-inspired models of computation

The most established "classical" nature-inspired models of computation are cellular automata, neural computation, and evolutionary computation. More recent computational systems abstracted from natural processes include swarm intelligence, artificial immune systems, membrane computing, and amorphous computing.

- a. Cellular Automata: A cellular automaton is a dynamical system consisting of a regular grid of cells, in which space and time are discrete. Each of the cells can be in one of a finite number of states. Each cell changes its state according to a list of given transition rules that determine its future state, based on its current state and the current states of some of its neighbors. The entire grid of cells updates its configuration synchronously according to the *a priori* given transition rules. Cellular automata have been applied to the study of phenomena as diverse as communication, computation, construction, growth, reproduction, competition, and evolution.
- b. Neural Computation (neural networks): Neural computation is the field of research that emerged from the comparison between computing machines and the human nervous system. This field aims both to understand how the brain of living organisms works (brain theory or computational neuroscience), and to design efficient algorithms based on the principles of how the human brain processes information (Artificial Neural Networks, ANN).
- c. Evolutionary Computation (genetic algorithms, genetic programming): Evolutionary computation is a computational paradigm inspired by Darwinian evolution. An artificial evolutionary system is a computational system based on the notion of simulated evolution. It comprises a constant- or variable-size population of individuals, a fitness criterion, and genetically inspired operators that produce the next generation from the current one.
- d. Swarm Intelligence (particle swarm optimization, ant algorithms): A swarm is a group of mobile biological organisms (such as bacteria, ants, termites, bees, spiders, fish, birds) wherein each individual communicates with others either directly or indirectly by acting on its local environment. These interactions contribute to distributive collective problem solving. Swarm intelligence, sometimes referred to as collective intelligence, is defined as the problem-solving behavior that emerges from the interaction of such a collection of individual agents.
- e. Artificial Immune Systems: Artificial immune systems (a.k.a. immunological computation or immunocomputing) are computational systems inspired by the natural immune systems of biological organisms. Viewed as an information processing system, the natural immune system of organisms performs many complex tasks in parallel and distributed computing fashion. These include distinguishing between self and nonself, neutralization of nonself pathogens (viruses, bacteria, fungi, and parasites), learning, memory, associative retrieval, self-regulation, and fault-tolerance. Artificial immune systems are abstractions of the natural immune system, emphasizing these computational aspects. Their applications include computer virus detection, anomaly detection in a time series of data, fault diagnosis, pattern recognition, machine learning, bioinformatics, optimization, robotics and control.

- f. **Artificial Life (Lindenmayer systems, mechanical artificial life, artificial chemistry):** Artificial life (ALife) is a research field whose ultimate goal is to understand the essential properties of life organisms by building, within electronic computers or other artificial media, ab initio systems that exhibit properties normally associated only with living organisms. Early examples include Lindenmayer systems (L-systems) that have been used to model plant growth and development.
- g. **Membrane Computing:** Membrane computing investigates computing models abstracted from the compartmentalized structure of living cells effected by membranes. A generic membrane system (P-system) consists of cell-like compartments (regions) delimited by membranes, that are placed in a nested hierarchical structure. Each membrane-enveloped region contains objects, transformation rules which modify these objects, as well as transfer rules, which specify whether the objects will be transferred outside or stay inside the region. Regions communicate with each other via the transfer of objects. Applications of membrane systems include machine learning, modelling of biological processes (photosynthesis, certain signaling pathways, quorum sensing in bacteria, cell-mediated immunity), as well as computer science applications such as computer graphics, public-key cryptography, approximation and sorting algorithms
- h. **Amorphous Computing:** In biological organisms, morphogenesis (the development of well-defined shapes and functional structures) is achieved by the interactions between cells guided by the genetic program encoded in the organism's DNA. Inspired by this idea, amorphous computing aims at engineering well-defined shapes and patterns, or coherent computational behaviours, from the local interactions of a multitude of simple unreliable, irregularly placed, asynchronous, identically programmed computing elements (particles). Amorphous computing also plays an important role as the basis for "cellular computing."

2. Nature as Implementation Substrate:

All of the computational techniques mentioned above, while inspired by nature, have been implemented until now mostly on traditional electronic hardware. In contrast, the two paradigms introduced here, molecular computing and quantum computing, employ radically different types of hardware.

- a. **Molecular (DNA) Computing:** Molecular computing (a.k.a. biomolecular computing, biocomputing, biochemical computing, DNA computing) is a computational paradigm in which data is encoded as biomolecules such as DNA strands, and molecular biology tools act on the data to perform various operations (e.g., arithmetic or logical operations).
- b. **Quantum Computing:** A quantum computer processes data stored as quantum bits (qubits), and uses quantum mechanical phenomena such as superposition and entanglement to perform computations.

3. Nature as Computation

The dual aspect of natural computation is that it aims to understand nature by regarding natural phenomena as information processing.

- a. **Systems Biology (Computational systems biology, gene regulatory networks, biochemical networks, transport networks):** Computational systems biology (or simply systems biology) is an integrative and qualitative approach that investigates the complex communications and interactions taking place in biological systems. Thus, in systems biology, the focus of the

study is the interaction networks themselves and the properties of biological systems that arise due to these networks, rather than the individual components of functional processes in an organism. This type of research on organic components has focused strongly on four different interdependent interaction networks: gene-regulatory networks, biochemical networks, transport networks, and carbohydrate networks.

- b. Synthetic Biology (artificial organisms, cell-to-cell communication): Synthetic biology aims at engineering synthetic biological components, with the ultimate goal of assembling whole biological systems from their constituent components.
- c. Cellular Computing (in vivo computing): Another approach to understanding nature as computation is the research on computation in living cells. This is also sometimes called cellular computing, or in vivo computing