

Encyclopedia of Computer Science

FOURTH EDITION

Editors:

Anthony Ralston
Edwin D. Reilly
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Encyclopedia of Computer Science
Fourth Edition
Edited by Anthony Ralston, Edwin D. Reilly and David Hemmendinger

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Preface to the Fourth Edition

It is now seven years since the publication of the third edition of this *Encyclopedia*. In the Preface to the third edition it was noted that the pace of change in computing "is still more rapid than in any other scientific or technical discipline," but that it "may not be as breakneck as it once was." The former claim is still correct; the latter, however, probably is not. The advent of the Internet and the rapidly falling prices and increasing capability of personal computers, among other things, made the 1990s a period of very rapid change indeed. Thus seven years is such a long time between editions that this is a very different volume from its predecessors.

How different? The third edition contained 605 articles from 370 contributors (compared with 550 and 301 in the second edition and 470 and 210 in the first edition). This edition has 623 articles from over 450 contributors of which

- ◆ 103 are new articles
- ◆ 29 are rewritten articles on subjects covered in the third edition
- ◆ 132 are third edition articles that have been extensively modified and brought up to date.

Also, this edition has 16 color pages whereas the third edition, the first to have any color at all, had only 12.

As in the previous editions, in addition to articles on the history of computing itself, many articles discuss the history of their subjects. There are five new biographies of major figures in computing, but we have

adopted a policy of not adding any new biographies of living people. There are also new articles on the history of nine important programming languages. Almost all articles from the third edition that have been retained have undergone at least minor modification, and many were extensively revised or replaced. In order that the size of the fourth edition be not too much greater than that of the third, some articles from that edition have been merged into other articles while others have been deleted because their subject matter was deemed both obsolete and not of historical significance.

The seven appendices in the third edition have been retained, and two new ones have been added. One lists all articles in earlier editions that no longer appear, so that readers can find certain topics not covered in this edition. The other lists the presidents of various professional societies; previous editions included them in separate articles. The expanded Appendix IX, the Timeline of Significant Computing Milestones, remains, we hope, both informative and irreverent.

The overall result is a fourth edition in which over 40% of the material was either not contained in the third edition or has been significantly modified. The Classification of Articles in the front of this volume is an important tool for readers looking for subject matter in a specific area. In addition, there are two extensive indexes, a Subject Index and a Name Index. The latter contains the names of all persons mentioned somewhere in the *Encyclopedia* (except for authors of uncited items in bibliographies).

It is intended to make this edition available by subscription on the World Wide Web. And because current technology makes it easy and affordable, we hope to update the Web edition regularly to provide a more up-to-date resource than a printed book can ever be. This updated edition will then be used to publish fifth (and later!) editions. Indeed, before too long—but probably not for the fifth edition—this *Encyclopedia* may become entirely electronic.

Finally, a word about the title. It is the same as that of the first and third editions, whereas the second was called *The Encyclopedia of Computer Science and Engineering*. In the preface to the third edition it was light-heartedly suggested that we would henceforth use “Engineering” in the even numbered editions and omit it from the odd-numbered editions. The engineering aspects of computing, both hardware and soft-

ware, are fully represented in this edition, but we have chosen to retain the more succinct title of the third edition.

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NOTE: The editors and publisher welcome comments on how this *Encyclopedia* could be improved in both coverage and style as well as reports on any errors of fact or typographical errors. All correspondence should be sent by email to one of the addresses above or by snailmail to Editors, *Encyclopedia of Computer Science*, Macmillan Reference Ltd, 25 Eccleston Place, London SW1W 9NF, UK.

— Editor's Foreword —

The most important purpose of an encyclopedia in a particular discipline is to be a basic reference work for readers who need information on subjects in which they are not expert. The implication of "basic" is that an encyclopedia, while it should attempt to be comprehensive in *breadth* of coverage, cannot be comprehensive in the *depth* with which it treats most topics. An encyclopedia should, however, direct the reader to information at a deeper level, as this one does through bibliographic references and cross-references to other articles. In this edition for the first time many articles also list pertinent Websites (but the reader should be warned: uniform resource locators for Websites are often ephemeral so that the fraction of those in this *Encyclopedia* that are accurate will decline with time).

What constitutes breadth of coverage is always a difficult question, and it is especially so for computer science and computer engineering, relatively new disciplines that have evolved over the past five decades and are still changing rapidly. Their boundaries are not well defined because there is no general agreement, even among computer scientists and technologists, as to whether certain areas are or are not part of these disciplines. Thus the choice of specific topics for this *Encyclopedia* has required our judgment of what is basic and important, modulated by the practical problems of finding appropriate authors to write the articles. While there may be disagreement about the inclusion or exclusion of certain topics, we hope and believe that little of major importance has been omitted.

Articles in this *Encyclopedia* normally contain definitions of the article titles (typically early in the article in a sentence or paragraph where the article title is italicized), but even the shortest articles also contain explanatory information to broaden and deepen the reader's understanding. There are numerous historical articles, and long articles contain historical and survey material that integrate the subject matter and put it into perspective. Overall, the encyclopedia is a general reference to computer science and engineering, as well as a broad picture of the discipline, its history, and its direction.

Organization

The organization of this volume is alphabetical by article titles. Special characters collate in accord with their ASCII sequence except that hyphens are treated as spaces. Thus, for example, COMPUTER-AIDED SOFTWARE ENGINEERING comes before COMPUTER ALGEBRA. Titles have been chosen so that the first word is generally the one most likely to be selected by the reader searching for a given topic. In addition, there are cross-reference entries when the reader might have sought more than one word in a title, or when the article could have been given an alternative synonymous title.

There are five additional aids to the reader. The first aid is the Classification of Articles, which follows this Foreword. This classification is intended to guide the reader to clusters of related articles. It may also be

useful in helping readers to follow a coherent self-study regime in a particular subfield. The second such aid is the list of cross-references at the beginning of each article, which cite titles of closely related articles, and the third aid is the frequent use of the notations (*q.v.*) and "See" in articles to indicate the title of an article related to the point under discussion.

The nine appendices at the back of the book constitute the fourth aid. These are abbreviations and acronyms; notation; journals and magazines relevant to computing; academic departments of computer science and engineering; presidents of computer societies; computer languages; a five-language glossary of important computer terms; articles in prior editions deleted from this one; and an extensive timeline of important milestones in computing.

The fifth aid is the pair of indexes. In a dictionary or glossary, all terms being defined appear as entries,

making an index superfluous. But in an encyclopedia only the most important terms are used as article titles or even main cross-references, making an index essential. We have tried to make the General Index comprehensive but to make it easier to use, we have placed most references to people in a separate Name Index that precedes the General Index. The General Index contains all terms that should appear in a *dictionary* of computer science, but also contains entries that would not normally appear in a computer dictionary, such as references to subcategories and important words in general usage. Thus the index will often provide pointers to unfamiliar terms whose exploration the reader might find useful and interesting.

Anthony Ralston

Edwin D. Reilly

David Hemmendinger

Classification of Articles

This classification of articles embodies a taxonomy that should be helpful to the reader in grasping the scope of the material contained in this volume. Articles are classified under nine categories:

1. Hardware
2. Computer Systems
3. Information and Data
4. Software
5. Mathematics of Computing
6. Theory of Computation
7. Methodologies
8. Applications
9. Computing Milieux

Each Encyclopedia article appears at least once in this classification. Some titles appear more than once in order to avoid the clutter of cross-references. Most classification headings are themselves article titles, in which case the title is followed by the page on which it begins. Headings preceded by an asterisk (*), however, are not actual titles but rather were invented to provide coherence to the classification. (Note: Appendix VIII contains a list of all articles in previous editions that are not in this edition.)

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Item	Article	Owner
A+	Personnel in the Computer Field	Computing Technology Industry Association
Access	Personnel in the Computer Field	Microsoft
ACSL	Simulation	MGA Software
Alpha	Intermediate Languages	Digital Equipment Corporation
Amphion	Automatic Programming	NASA
Aptiva	IBM PC	IBM
Axiom	Computer Algebra: Systems	Numerical Algorithms Group
BONeS Designer	Simulation	Alta Group
Buddy List	Online Conversation	AOL
Capability Maturity Model	Software Engineering Institute	Software Engineering Institute
CERT	Software Engineering Institute	Software Engineering Institute
Chem	Computer Science	NASA
COMNET III	Simulation	CACI Products
Corel Amicus Attorney	Legal Applications	Gavel and Gown Software Inc.
CPSim	Simulation	BoyanTech
CPUMark99	Benchmarks	Ziff-Davis, Inc.
CSIM18	Simulation	Mesquite Software
DataGlove	Virtual Reality	VPL Research
DB-2	Computer Science	IBM
dBase	Computer Science	dBASE, Inc.
DECNET	Computer Science	Digital Equipment Corporation
Derive	Computer Algebra: Systems	Soft Warehouse
Eispack	Computer Science	Netlib
Excel	Software History	Microsoft
Extend	Simulation	Imagine That
FLAMES	Simulation	Ternion
GPSS/H	Standards	Wolverine Software
HotDocs	Legal Applications	Capsoft Development
Hypercard	Computer Science	Apple Computer, Inc.
IBM PC	Intermediate Languages	IBM
ICQ	Online Conversation	Mirabalís
Ingres	Computer Science	Computer Associates
Instant Messaging	Online Conversation	AOL
Intel Pentium	Microcomputer Chip	Intel
Intel 486	Microcomputer Chip	Intel
Intermedia	Computer Science	Intermedia Communications
ITEMS	Simulation	CAE Electronics

Item	Article	Owner
Java	Java (and many others)	Sun Microsystems
Jaz	Memory: Auxiliary	Iomega Corporation
JFS Docket Station	Legal Applications	Bowne & Co.
JFS JazzNotes	Legal Applications	Bowne & Co.
JFS Litigator's Notebook	Legal Applications	Bowne & Co.
Lego	LOGO	Lego Company
Linpack	Computer Science	Netlib
listserv	Electronic Mail	L-Soft International
Lotus 1-2-3	Software History	Lotus
Mach	Computer Science	Carnegie Mellon University
Macintosh	Windows Environments (and many others)	Apple Computer, Inc.
MacOS	Computer Science	Apple Computer, Inc.
Macsyma	Computer Algebra: Systems	Macsyma, Inc.
Majordomo	Electronic Mail	Great Circle Associates
Maple	Computer Science <i>and</i> Mathematics, Computers In <i>and</i> Computer Algebra: Systems	Waterloo Maple, Inc.
Mathematica	Computer Science <i>and</i> Mathematics, Computers In	Wolfram Research, Inc.
Metafont	Metafont	Addison-Wesley Publishing Co.
Microsoft Messenger	Online Conversation	Microsoft
Microsoft Word	Text Editing Systems	Microsoft
MODSIM	Simulation	CACI Products
MPIOC	Input-Output Operations	MasPar
MS-DOC	Computer Science	Microsoft
Multi-Edit	Text Editing Systems	American Cybernetics
Multics	Computer Science	Honeywell
MultiGenII	Simulation	Multigen
MuPAD	Computer Algebra: Systems	Sciface Software GmbH
NLS	Computer Science	Stanford Research Institute
NoteCards	Computer Science	Xerox
Omnipage Pro	Optical Character Recognition	Caere Corporation
OS/2	Computer Science	IBM
Personal Software Process	Software Engineering Institute	Software Engineering Institute
PlanWare	Automatic Programming	Invest-Tech, Ltd.
Portège	Portable Computers	Toshiba
Powerbuilder	Personnel in the Computer Field	Sybase, Inc.
Quattro Pro	Software History	Corel Corporation
RealAudio	Bulletin Board	Real Networks, Inc.
RealVideo	Bulletin Board	Real Networks, Inc.
SAS System	Access methods	SAS Institute
SciNapse	Automatic Programming	SciComp, Inc.
Silicon Graphics 320	Workstation	Silicon Graphics Inc.
SIMAN/Cinema	Simulation	Systems Modeling
SIMGRAPHICS	Simulation	CACI Products
SimPack	Simulation	University of Florida
Simscrip II.5	Simulation	CACI Products
SLAM II	Simulation	Pritsker Associates
Sparc	Intermediate Languages	Sun Microsystems
SuperCard	Computer Science	Digital Media Group, Ltd.
Sybase	Computer Science	Sybase, Inc.
SYSmark	Benchmarks	BAPCo
System R	Computer Science	IBM
Taylor II	Simulation	F&H Simulations
TEX	TEX	American Mathematical Society
Thinkpad	IBM PC	IBM
Unix	Unix (and many others)	AT&T Bell Laboratories
Virtual Basic	Basic	Microsoft
Virtual Classroom	Computer Conferencing	New Jersey Institute of Technology
Visicalc	Software History	Trellix Corporation
Visual Basic	Personnel in the Computer Field	Microsoft
VMS	Computer Science	Digital Equipment Corporation
VRLink	Simulation	MAK Technologies
Web	Computer Science	NASA
WinBench	Benchmarks	Ziff Davis, Inc.

Item	Article	Owner
Windows	Text Editing System (and many others)	Microsoft
Windows NT	Computer Science	Microsoft
Winstone	Benchmarks	Ziff Davis, Inc.
Workbench	Simulation	SES
Xanadu	Computer Science	NASA
Yahoo! Messenger	Online Conversation	Yahoo!
Zip	Memory: Auxiliary	Iomega Corporation
Zip + 4	Optical Character Recognition	US Postal Service

MOBILE COMPUTING

For articles on related subjects see COMMUNICATIONS AND COMPUTERS; NETWORKS, COMPUTER; and PORTABLE COMPUTERS.

Mobile computing is computing using a device that can communicate through a wireless channel. The field of mobile computing is as broad as traditional computing. Consumers expect the same convenience and computing power in the mobile device as in the computer which sits on the desk. Furthermore, mobility opens up new venues for interesting and unique products and services. Freedom from geographic constraints can allow a more effective, convenient, and timely use of computing and communication. As people tend to think and work in places other than at their office desks, mobile computing lets the computer be used as a tool where it is needed, not where it is tied by a wire. Examples include the executive working on a laptop while traveling and the field engineer having remote electronic access to technical documentation and diagnostics, as well as emerging applications such as automated inventory or baggage checking with RFID (Radio Frequency Identification Devices), and location-dependent services such as local maps or weather reports.

The combination of the rapid reduction in computing device sizes, small portable displays and wireless networking capabilities has fostered the growing interest in *wearable computers*. Emerging experimental systems are small enough to be mounted on belts or helmets and often provide as much processing and networking power as their desktop counterparts. Besides the obvious capabilities for browsing the World Wide Web (*q.v.*) while performing mundane tasks, these "wearables" foster the creation of computer-mediated reality. Applications such as technicians having field manuals projected through glasses while they are working on a device, and computer-assisted facial recognition for instantly matching contact information with faces are just two examples of applications motivated by these devices. Similar applications have been proposed as computer resources for the disabled (*see* DISABLED, COMPUTERS AND THE). For example, there have been experiments with a wearable computer equipped with a camera and running a neural network (*q.v.*) program to recognize American Sign Language (ASL) and translate it into English for the benefit of the wearer who does not know ASL. Such wearable computers could also draw on the resources of more powerful ones through an Internet (*q.v.*) connection.

Several years ago mobile computing was defined in terms of the laptops used. However, this traditional view has changed significantly. Cellular phones already

allow Web browsing and email reception, palmtop computers come with scaled-down versions of desktop operating systems and applications, and RFID devices provide intelligent communication and computing power with nearly any type of object. This myriad of new devices spans the technological and budgetary spectrums.

The explosion in mobile computing has been made possible through advances in certain key technological areas. Consider the relationships between mobility, portability, ergonomics, and cost. For example, in order to make a device portable it must be small and lightweight, which precludes the use of most standard hard drive and keyboard designs. Second, a fundamental requirement of today's computer is network connectivity. This generally calls for radio-frequency wireless communications for mobile devices. Although infrared mobile computer communications can also be used, interference from the Sun as well as the difficulty of non-line-of-sight communications make radio-frequency the preferred method for location-independent mobile communications. Third and most important are power considerations. Mobility requires a portable power source: a battery. Since battery power depends on size and weight, it is essential that all the parts of the mobile device are power-efficient. As battery capacities are not expected to increase by more than 30% in the near future (Powers, 1995), while computing capabilities and features have ever-increasing expectations, power efficiency has become a fundamental technology.

Mobility, Portability, and Utility

Mobile computing has benefited greatly from the advances in many areas of technology. High-density VLSI fabrication techniques, heat dissipation, and increased hard drive densities are examples of progress seen on the desktop which have also boosted the feasibility of mobile computing. The following are some of the more important areas of future device design (Harris *et al.*, 1995):

- ◆ *Display devices* Mobile devices which provide interaction with people require some sort of display device for feedback. In laptop computers, the design goal is usually to have displays which can provide the same resolution, refresh rate, and color capabilities as the desktop version in a screen which is less than an inch thick. Color liquid crystal is the most popular for this use but requires about 50% of the power of the entire mobile. Other mobile devices, such as Apple's Newton, are experimenting with different types of display designed specifically for their applications.

- ◆ *Integrated circuits* The most important part of the mobile computer, the CPU, is about the size of a thumbnail. Even with this high level of integration, advances are still being achieved in wireless transmitters, where items such as inductors are especially difficult to fabricate on a silicon die. Power also becomes a major issue, since the power required by the chip increases with the clock frequency.
- ◆ *Hard drive and other storage* As with integrated circuits, the density of hard drives has increased dramatically through the years. Typical methods to reduce the power consumed by these is to stop the rotation of the disk platter when it is not in use. Solid-state storage devices such as *flash memory* (a kind of reprogrammable ROM—*q.v.*) have also become very popular for mass storage as they require very low amounts of power and physical space.
- ◆ *Input devices* Input devices must also become smaller for the sake of mobility. Unlike traditional phones, where the minimum size is limited only by the ear-to-mouth distance, the input and output facilities of mobile computers still need to be large enough to be convenient to operate. One method of coping with this constraint is to combine the input and output facilities into a touch screen, such as the Apple Newton and AT&T's EO.

Mobile Networking

From the emergence of network-oriented languages such as Java (*q.v.*) to the legislatively encouraged convergence of communication technologies, communications has become an essential requirement of computing today. Mobile computing is no exception to this, with the additional challenge of utilizing the radio-frequency bandwidth (*q.v.*). When radio frequency signals are transmitted, they are reflected, refracted, and scattered by many objects on their way to the receiver. The resulting received signal is a combination of all of these paths, so that the phase and amplitude of the received signal can change drastically from even slight movements of the mobile or the surrounding objects. This time-varying random process, termed *multipath fading*, creates a potentially very high error rate on data being transferred to the mobile device, which can be significantly worse than that encountered in wired networks (Pahlavan and Levesque, 1995). There are a variety of methods used to combat these effects, including special error correcting and detecting codes (*q.v.*) added to each packet, spreading the packet's bits across multiple packets or frequencies, and enhanced modulation schemes.

There are three basic methods to connect a wireless computer to the rest of the world. All of these assume

the existence of a wired base station infrastructure. Satellite communication may be possible as well, but it is typically extremely power-intensive. The first method is to use a modem (*q.v.*) over a voice-grade cellular phone. This is analogous to the way most people connect to the Internet (*q.v.*) from their homes by dialing to an Internet Service Provider (ISP) over a standard voice-grade line. Second, Mobitex and ARDIS are two examples of dedicated packet data networks which are emerging to meet the demand for higher efficiency and data rates than analog modems over radio can provide. Lastly, a hybrid of these two approaches uses the cellular networks designed for voice for transmitting packet data (see PACKET SWITCHING). CDPD (Cellular Digit Packet Data) is a system which uses idle voice channels on the analog AMPS voice cellular system to transmit data. Additionally, the newest digital cellular systems such as GSM (Global System for Mobile Communications) also include provisions for multiplexing packet data for transmission with digitized speech. Communication between mobile nodes without a base station as an intermediary is also possible and is termed *ad hoc* (improvised) networking. This method requires that some or all of the mobile nodes act as packet routers, and that the network protocols be robust enough to handle frequent, random topology changes as the nodes move (Corson and Macker, 1997).

In traditional desktop computing, the topology of the network is static. The physical location of the machine is encoded into its network address in protocols (*q.v.*) such as TCP/IP (*q.v.*). In the mobile network, the topology can be constantly changing as the devices move from cell to cell. The questions of how to change routing policies, update node addressing, and maintain mobile device location information are actively researched areas. An example of a protocol which does this while attempting to maintain compatibility with the existing Internet protocols is Mobile IP (Perkins, 1998).

The severely limited bandwidth is another fundamental challenge that mobile communications must consider. The part of the radio frequency spectrum usable for communications is limited and must be shared with television, radio, military, satellite communications, and many other services. Therefore, the frequency band available for mobile computer communication is extremely small when compared with that of a wire connected to a desktop computer. The challenge to mobile computing is to maintain high data rates in the presence of high errors while still maintaining fair access to a multitude of subscribers.

It is important that the wireless communication link not drastically deplete the mobile computer of its power.

Two areas are actively addressed: reducing the power used by the transceiver circuitry when it is on, or simply turning the transceiver off when it is not expected to be used. The latter method affects the mobile network in other ways, such as adding to the amount of delay experienced by a packet that is to be transmitted from the base station. Energy-conserving protocols (*q.v.*) such as those in Chlamtac *et al.* (1998) are designed to allow the mobile node to turn "off" the transceiver at deterministic times such that the base station can predict when the mobile is capable of receiving a packet. In the presence of a potentially very high node density and nonuniform traffic, the protocols allow a variable trade-off between the frequency of "on" time (and therefore consumed energy) and the amount of time before a packet can be transmitted from the base station. Similarly, the protocols in Imielinski *et al.* (1996) support energy-conservation in a mobile network where the basestation periodically transmits large amounts of broadcast data such as news or stock quotes. These protocols intelligently organize the data with a directory so the mobile can reduce the amount of time that its receiver is "on" while watching the broadcast for the data of interest.

Conclusions

If success in the computing field is defined by market share and consumer interest, there is no question that mobile computing has already exceeded most expectations and is well on its way toward becoming one of the dominant forces of the entire information industry. From the array of palmtop computers available in budget superstores, to Intel's release of low-power mobile-oriented Pentium chips nearly immediately after the desktop version release, to the exorbitant sums of money paid by cellular operators for leasing radio towers and buying frequency space, there is little doubt about the potential of ubiquitous mobile computing. The challenges are complex, interrelated, and exacerbated by often hard, physical limitations (such as the limited RF bandwidth). However, if we try to gage the innovative potential of the computer industry by its past performance, it appears that that we have only begun to see the future of mobile computing.

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Imre Chlamtac and Jason Redi

MODEL CHECKING

For articles on related subjects see FORMAL METHODS FOR COMPUTER SYSTEMS; HARDWARE VERIFICATION; LOGICS OF PROGRAMS; and PROGRAM VERIFICATION.

Model checking is a technique of automatically verifying logical properties of the behavior of finite state systems. These properties are expressed in *temporal logic* (Burgess, 1984), a class of logics that is well suited to specifying the relationship of events in time. For example, in temporal logic, one can readily specify that condition *p* must eventually be followed by condition *q*, or that, after *p*, condition *q* must hold until the next occurrence of *r*, and so forth. A model checker determines whether a given finite state model satisfies a formula in the logic. In the negative case, it can supply a counterexample, that is, a behavioral trace that shows that the specified formula is false.

Model checking has been most successfully applied to the verification of computer hardware designs. This is because significant portions of a typical hardware design can be effectively modeled as a finite state transition system. As an example, model checkers have proved very effective at finding errors in the cache coherence (*q.v.*) protocols of multiprocessor systems. These errors tend to escape detection by simulation (*q.v.*), due to the infrequency of their occurrence.

Temporal Logic

In a propositional temporal logic, the usual operators of propositional logic (see BOOLEAN ALGEBRA and DISCRETE MATHEMATICS) are augmented by *tense operators*, which are used to form statements about how conditions change in time. For example, the formula *Fq* is true in the present if *q* is true at some moment in the future. The formula *Gq* is true in the present if *q* is true at *all* moments in the future. These operators can be combined to express more complex relationships. For example, the formula *G(p ⇒ Fq)* can be read as "at all future times, if *p* holds, then *q* must hold at some later time." In the context of a hardware design, *p* might be