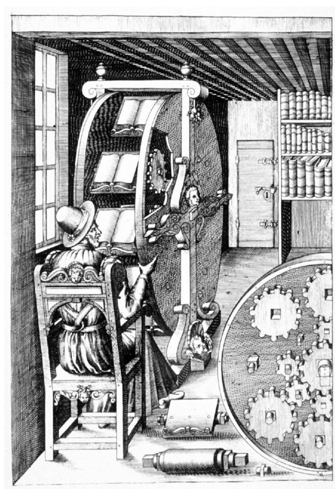
Structure and Interpretation *of* Computer Programs



SECOND EDITION

Unofficial Texinfo Format 2.andresraba5.6

Harold Abelson and
Gerald Jay Sussman
with Julie Sussman

foreword by Alan J. Perlis

Structure and Interpretation of Computer Programs,
second edition

Harold Abelson and Gerald Jay Sussman
with Julie Sussman, foreword by Alan J. Perlis

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Contents

Unofficial Texinfo Format

This is the second edition SICP book, from Unofficial Texinfo Format.

You are probably reading it in an Info hypertext browser, such as the Info mode of Emacs. You might alternatively be reading it TeX-formatted on your screen or printer, though that would be silly. And, if printed, expensive.

The freely-distributed official HTML-and-GIF format was first converted personally to Unofficial Texinfo Format (UTF) version 1 by Lytha Ayth during a long Emacs lovefest weekend in April, 2001.

The UTF is easier to search than the HTML format. It is also much more accessible to people running on modest computers, such as donated '386-based PCs. A 386 can, in theory, run Linux, Emacs, and a Scheme interpreter simultaneously, but most 386s probably can't also run both Netscape and the necessary X Window System without prematurely introducing budding young underfunded hackers to the concept of *thrashing*. UTF can also fit uncompressed on a 1.44MB floppy diskette, which may come in handy for installing UTF on PCs that do not have Internet or LAN access.

The Texinfo conversion has been a straight transliteration, to the extent possible. Like the TeX-to-HTML conversion, this was not without some introduction of breakage. In the case of Unofficial Texinfo Format, figures have suffered an amateurish resurrection of the lost art of ASCII. Also, it's quite possible that some errors of ambiguity were introduced during the conversion of some of the copious superscripts ('^') and subscripts ('_'). Divining *which* has been left as an exercise to the reader. But at least we don't put our brave astronauts at risk by encoding the *greater-than-or-equal* symbol as <u>></u>.

If you modify `sicp.texi` to correct errors or improve the ASCII art, then update the `@set utfversion 2.andresraba5.6` line to reflect your delta. For example, if you started with Lytha's version `1`, and your name is Bob, then you could name your successive versions `1.bob1`, `1.bob2`, ... `1.bob`*n*. Also update `utfversiondate`. If you want to distribute your version on the Web, then embedding the string "sicp.texi" somewhere in the file or Web page will make it easier for people to find with Web search engines.

It is believed that the Unofficial Texinfo Format is in keeping with the spirit of the graciously freely-distributed HTML version. But you never know when someone's armada of lawyers might need something to do, and get their shorts all in a knot over some benign little thing, so think twice before you use your full name or distribute Info, DVI, PostScript, or PDF formats that might embed your account or machine name.

Peath, Lytha Ayth

Addendum: See also the SICP video lectures by Abelson and Sussman: at MIT CSAIL or MIT OCW.

Second Addendum: Above is the original introduction to the UTF from 2001. Ten years later, UTF has been transformed: mathematical symbols and formulas are properly typeset, and figures drawn in vector graphics. The original text formulas and ASCII art figures are still there in the Texinfo source, but will display only when compiled to Info output. At the dawn of e-book readers and tablets, reading a PDF on screen is officially not silly anymore. Enjoy!

A.R, May, 2011

Dedication

THIS BOOK IS DEDICATED, in respect and admiration, to the spirit that lives in the computer.

> "I think that it's extraordinarily important that we in computer science keep fun in computing. When it started out, it was an awful lot of fun. Of course, the paying customers got shafted every now and then, and after a while we began to take their complaints seriously. We began to feel as if we really were responsible for the successful, error-free perfect use of these machines. I don't think we are. I think we're responsible for stretching them, setting them off in new directions, and keeping fun in the house. I hope the field of computer science never loses its sense of fun. Above all, I hope we don't become missionaries. Don't feel as if you're Bible salesmen. The world has too many of those already. What you know about computing other people will learn. Don't feel as if the key to successful computing is only in your hands. What's in your hands, I think and hope, is intelligence: the ability to see the machine as more than when you were first led up to it, that you can make it more."
>
> —Alan J. Perlis (April 1, 1922 – February 7, 1990)

Foreword

Educators, generals, dieticians, psychologists, and parents program. Armies, students, and some societies are programmed. An assault on large problems employs a succession of programs, most of which spring into existence en route. These programs are rife with issues that appear to be particular to the problem at hand. To appreciate programming as an intellectual activity in its own right you must turn to computer programming; you must read and write computer programs—many of them. It doesn't matter much what the programs are about or what applications they serve. What does matter is how well they perform and how smoothly they fit with other programs in the creation of still greater programs. The programmer must seek both perfection of part and adequacy of collection. In this book the use of "program" is focused on the creation, execution, and study of programs written in a dialect of Lisp for execution on a digital computer. Using Lisp we restrict or limit not what we may program, but only the notation for our program descriptions.

Our traffic with the subject matter of this book involves us with three foci of phenomena: the human mind, collections of computer programs, and the computer. Every computer program is a model, hatched in the mind, of a real or mental process. These processes, arising from human experience and thought, are huge in number, intricate in detail, and at any time only partially understood. They are modeled to our permanent satisfaction rarely by our computer programs. Thus even though our programs are carefully handcrafted discrete collections of symbols, mosaics of interlocking functions, they continually evolve: we change them as our perception of the model deepens, enlarges, generalizes until the model ultimately attains a metastable place within still another model with which we struggle. The source of the exhilaration associated with computer programming is the continual unfolding within the mind and on the computer of mechanisms expressed as programs and the explosion of perception they generate. If art interprets our dreams, the computer executes them in the guise of programs!

For all its power, the computer is a harsh taskmaster. Its programs must be correct, and what we wish to say must be said accurately in every detail. As in every other symbolic activity, we become convinced of program truth through argument. Lisp itself can be assigned a semantics (another model, by the way), and if a program's function can be specified, say, in the predicate calculus, the proof methods of logic can be used to make an acceptable correctness argument. Unfortunately, as programs get large and complicated, as they almost always do, the adequacy, consistency, and correctness of the specifications themselves become open to doubt, so that complete formal arguments of correctness seldom accompany large programs. Since large programs grow from small ones, it is crucial that we develop an arsenal of standard program structures of whose correctness we have become sure—we call them idioms—and learn to combine them into larger structures using organizational techniques of proven value. These techniques are treated at length in this book, and understanding them is essential to participation in the Promethean enterprise called programming. More than anything else, the uncovering and mastery of powerful organizational techniques accelerates our ability to create large, significant programs. Conversely, since writing large programs is very taxing, we are stimulated to invent new methods of reducing the mass of function and detail to be fitted into large programs.

Unlike programs, computers must obey the laws of physics. If they wish to perform rapidly—a few nanoseconds per state change—they must transmit electrons only small distances (at most $1\frac{1}{2}$ feet). The heat generated by the huge number of devices so concentrated in space has to be removed. An exquisite engineering art has been developed balancing between multiplicity of function and density of devices. In any event, hardware always operates at a level more primitive than that at which we care to program. The processes that transform our Lisp programs to "machine" programs are themselves abstract models which we program. Their study and creation give a great deal of insight into the organizational programs associated with programming arbitrary models. Of course the computer itself can be so modeled. Think of it: the behavior of the smallest physical switching element is modeled by quantum mechanics described by differential equations whose detailed behavior is captured by numerical approximations represented in computer programs executing on computers composed of . . .!

It is not merely a matter of tactical convenience to separately identify the three foci. Even though, as they say, it's all in the head, this logical separation induces an acceleration of symbolic traffic between these foci whose richness, vitality, and potential is exceeded in human experience only by the evolution of life itself. At best, relationships between the foci are metastable. The computers are never large enough or fast enough. Each breakthrough in hardware technology leads to more massive programming enterprises, new organizational principles, and an enrichment of abstract models. Every reader should ask himself periodically "Toward what end, toward what end?"—but do not ask it too often lest you pass up the fun of programming for the constipation of bittersweet philosophy.

Among the programs we write, some (but never enough) perform a precise mathematical function such as sorting or finding the maximum of a sequence of numbers, determining primality, or finding the square root. We call such programs algorithms, and a great deal is known of their optimal behavior, particularly with respect to the two important parameters of execution time and data storage requirements. A programmer should acquire good algorithms and idioms. Even though some programs resist precise specifications, it is the responsibility of the programmer to estimate, and always to attempt to improve, their performance.

Lisp is a survivor, having been in use for about a quarter of a century. Among the active programming languages only Fortran has had a longer life. Both languages have supported the programming needs of important areas of application, Fortran for scientific and engineering computation and Lisp for artificial intelligence. These two areas continue to be important, and their programmers are so devoted to these two languages that Lisp and Fortran may well continue in active use for at least another quarter-century.

Lisp changes. The Scheme dialect used in this text has evolved from the original Lisp and differs from the latter in several important ways, including static scoping for variable binding and permitting functions to yield functions as values. In its semantic structure Scheme is as closely akin to Algol 60 as to early Lisps. Algol 60, never to be an active language again, lives on in the genes of Scheme and Pascal. It would be difficult to find two languages that are the communicating coin of two more different cultures than those gathered around these two languages. Pascal is for building pyramids—imposing, breathtaking, static structures built by armies pushing heavy blocks into place. Lisp is for building organisms—imposing, breathtaking, dynamic structures built by squads fitting fluctuating myriads of simpler organisms into place. The organizing principles used are the same in both cases, except for one extraordinarily important difference: The discretionary exportable functionality entrusted to the individual Lisp programmer is more than an order of magnitude greater than that to be found within Pascal enterprises. Lisp programs inflate libraries with functions whose utility transcends the application that produced them. The list, Lisp's native data structure, is largely responsible for such growth of utility. The simple structure and natural applicability of lists are reflected in functions that are amazingly nonidiosyncratic. In Pascal the plethora of declarable data structures induces a specialization within functions that inhibits and penalizes casual cooperation. It is better to have 100 functions operate on one data structure than to have 10 functions operate on 10 data structures. As a result the pyramid must stand unchanged for a millennium; the organism must evolve or perish.

To illustrate this difference, compare the treatment of material and exercises within this book with that in any first-course text using Pascal. Do not labor under the illusion that this is a text digestible at MIT only, peculiar to the breed found there. It is precisely what a serious book on programming Lisp must be, no matter who the student is or where it is used.

Note that this is a text about programming, unlike most Lisp books, which are used as a preparation for work in artificial intelligence. After all, the critical programming concerns of software engineering and artificial intelligence tend to coalesce as the systems under investigation become larger. This explains why there is such growing interest in Lisp outside of artificial intelligence.

As one would expect from its goals, artificial intelligence research generates many significant programming problems. In other programming cultures this spate of problems spawns new languages. Indeed, in any very large programming task a useful organizing principle is to control and isolate traffic within the task modules via the invention of language. These languages tend to become less primitive as one approaches the boundaries of the system where we humans interact most often. As a result, such systems contain complex language-processing functions replicated many times. Lisp has such a simple syntax and semantics that parsing can be treated as an elementary task. Thus parsing technology plays almost no role in Lisp programs, and the construction of language processors is rarely an impediment to the rate of growth and change of large Lisp systems. Finally, it is this very simplicity of syntax and semantics that is responsible for the burden and freedom borne by all Lisp programmers. No Lisp program of any size beyond a few lines can be written without being saturated with discretionary functions. Invent and fit; have fits and reinvent! We toast the Lisp programmer who pens his thoughts within nests of parentheses.

Alan J. Perlis
New Haven, Connecticut

Preface to the Second Edition

> Is it possible that software is not like anything else, that it is meant to be discarded: that the whole point is to always see it as a soap bubble?
>
> —Alan J. Perlis

THE MATERIAL IN THIS BOOK has been the basis of MIT's entry-level computer science subject since 1980. We had been teaching this material for four years when the first edition was published, and twelve more years have elapsed until the appearance of this second edition. We are pleased that our work has been widely adopted and incorporated into other texts. We have seen our students take the ideas and programs in this book and build them in as the core of new computer systems and languages. In literal realization of an ancient Talmudic pun, our students have become our builders. We are lucky to have such capable students and such accomplished builders.

In preparing this edition, we have incorporated hundreds of clarifications suggested by our own teaching experience and the comments of colleagues at MIT and elsewhere. We have redesigned most of the major programming systems in the book, including the generic-arithmetic system, the interpreters, the register-machine simulator, and the compiler; and we have rewritten all the program examples to ensure that choice) by translating the explicit-control evaluator of Section 5.4 into C. In order to run this code you will need to also provide appropriate storage-allocation routines and other run-time support.

Exercise 5.52: As a counterpoint to Exercise 5.51, modify the compiler so that it compiles Scheme procedures into sequences of C instructions. Compile the metacircular evaluator of Section 4.1 to produce a Scheme interpreter written in C.

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3.11	3.12	3.13	3.14	3.15	3.16	3.17	3.18	3.19	3.20
3.21	3.22	3.23	3.24	3.25	3.26	3.27	3.28	3.29	3.30
3.31	3.32	3.33	3.34	3.35	3.36	3.37	3.38	3.39	3.40
3.41	3.42	3.43	3.44	3.45	3.46	3.47	3.48	3.49	3.50
3.51	3.52	3.53	3.54	3.55	3.56	3.57	3.58	3.59	3.60
3.61	3.62	3.63	3.64	3.65	3.66	3.67	3.68	3.69	3.70
3.71	3.72	3.73	3.74	3.75	3.76	3.77	3.78	3.79	3.80
3.81	3.82								

Chapter 4

4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.10
4.11	4.12	4.13	4.14	4.15	4.16	4.17	4.18	4.19	4.20
4.21	4.22	4.23	4.24	4.25	4.26	4.27	4.28	4.29	4.30
4.31	4.32	4.33	4.34	4.35	4.36	4.37	4.38	4.39	4.40
4.41	4.42	4.43	4.44	4.45	4.46	4.47	4.48	4.49	4.50
4.51	4.52	4.53	4.54	4.55	4.56	4.57	4.58	4.59	4.60
4.61	4.62	4.63	4.64	4.65	4.66	4.67	4.68	4.69	4.70
4.71	4.72	4.73	4.74	4.75	4.76	4.77	4.78	4.79	

Chapter 5

5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	5.10
5.11	5.12	5.13	5.14	5.15	5.16	5.17	5.18	5.19	5.20
5.21	5.22	5.23	5.24	5.25	5.26	5.27	5.28	5.29	5.30
5.31	5.32	5.33	5.34	5.35	5.36	5.37	5.38	5.39	5.40
5.41	5.42	5.43	5.44	5.45	5.46	5.47	5.48	5.49	5.50
5.51	5.52								

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> Any inaccuracies in this index may be explained by the fact that it has been prepared with the help of a computer.
>
> —Donald E. Knuth, *Fundamental Algorithms* (Volume 1 of *The Art of Computer Programming*)

Symbols

A

B

C

D

E

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H

N

O

P

Q

R

S

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U

V

W

Z

Colophon

On the cover page is Agostino Ramelli's bookwheel mechanism from 1588. It could be seen as an early hypertext navigation aid. This image of the engraving is hosted by J. E. Johnson of New Gottland.

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