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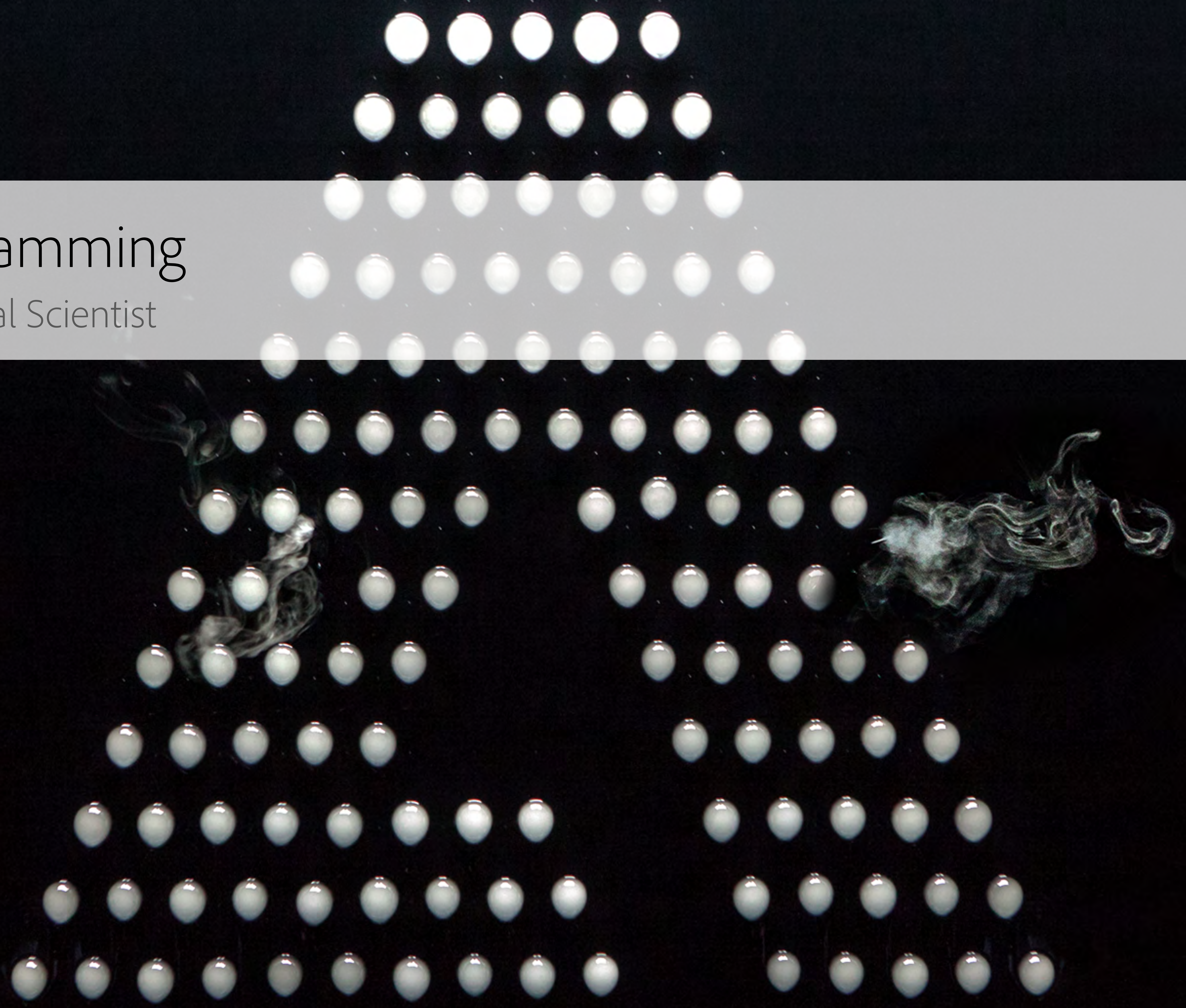
Generic Programming

Sean Parent | Principal Scientist



#AdobeRemix
Thomas Wirtz

"You cannot fully grasp mathematics until you understand its historical context." – Alex Stepanov

1988


T.S.
1989

1988

#1 Song: *Faith*, George Michael

#1 Movie: *Rain Man*

Winter Olympic Games in Calgary, Alberta, Canada

US Senate ratifies INF treaty between US and Soviet Union

    Ronald Regan & Mikhail Gorbachev

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Generic Programming*

David R. Musser†
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Computer Science Department
Amos Eaton Hall
Troy, New York 12180

Alexander A. Stepanov
Hewlett–Packard Laboratories
Software Technology Laboratory
Post Office Box 10490
Palo Alto, California 94303–0969

Abstract

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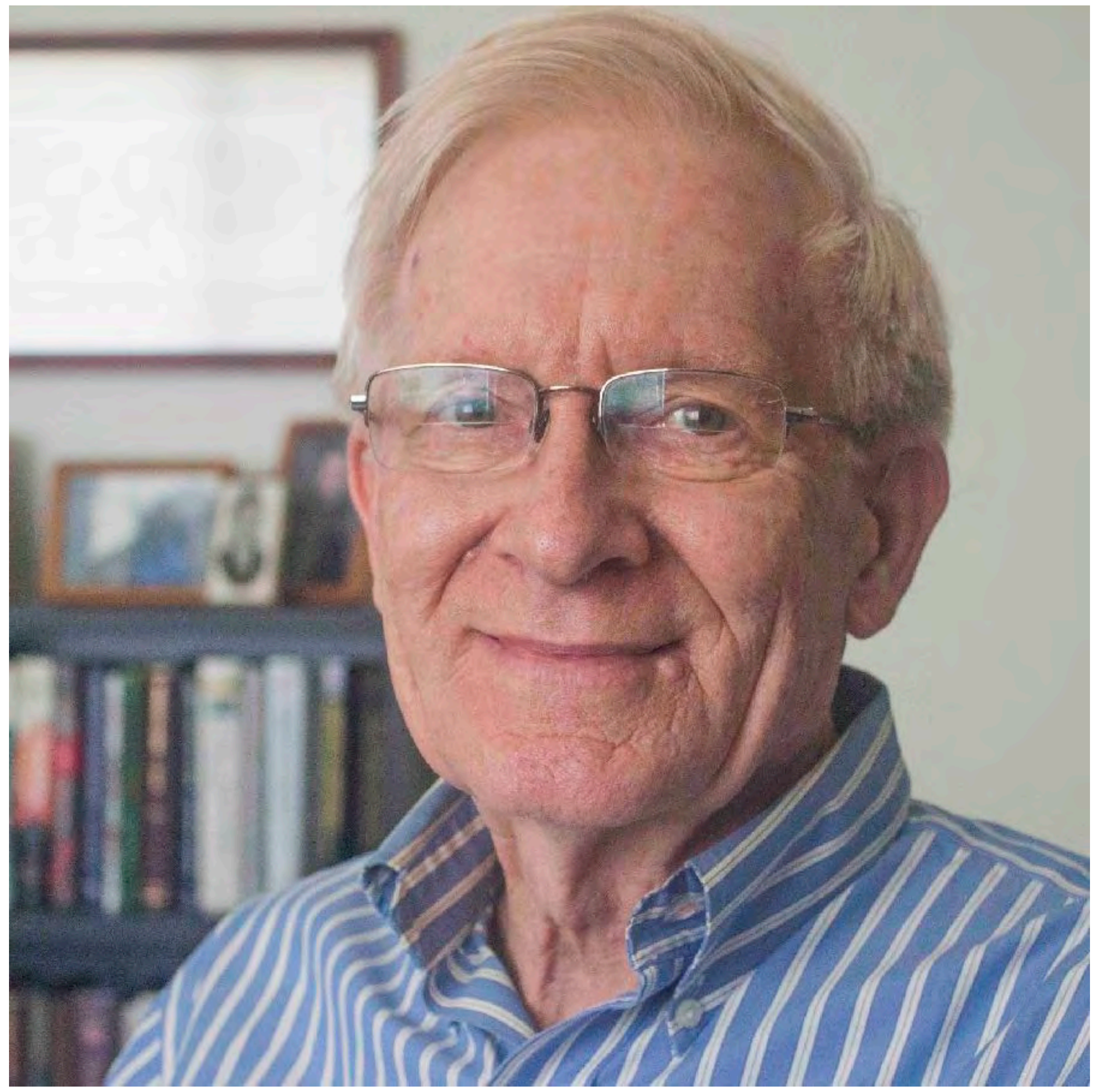

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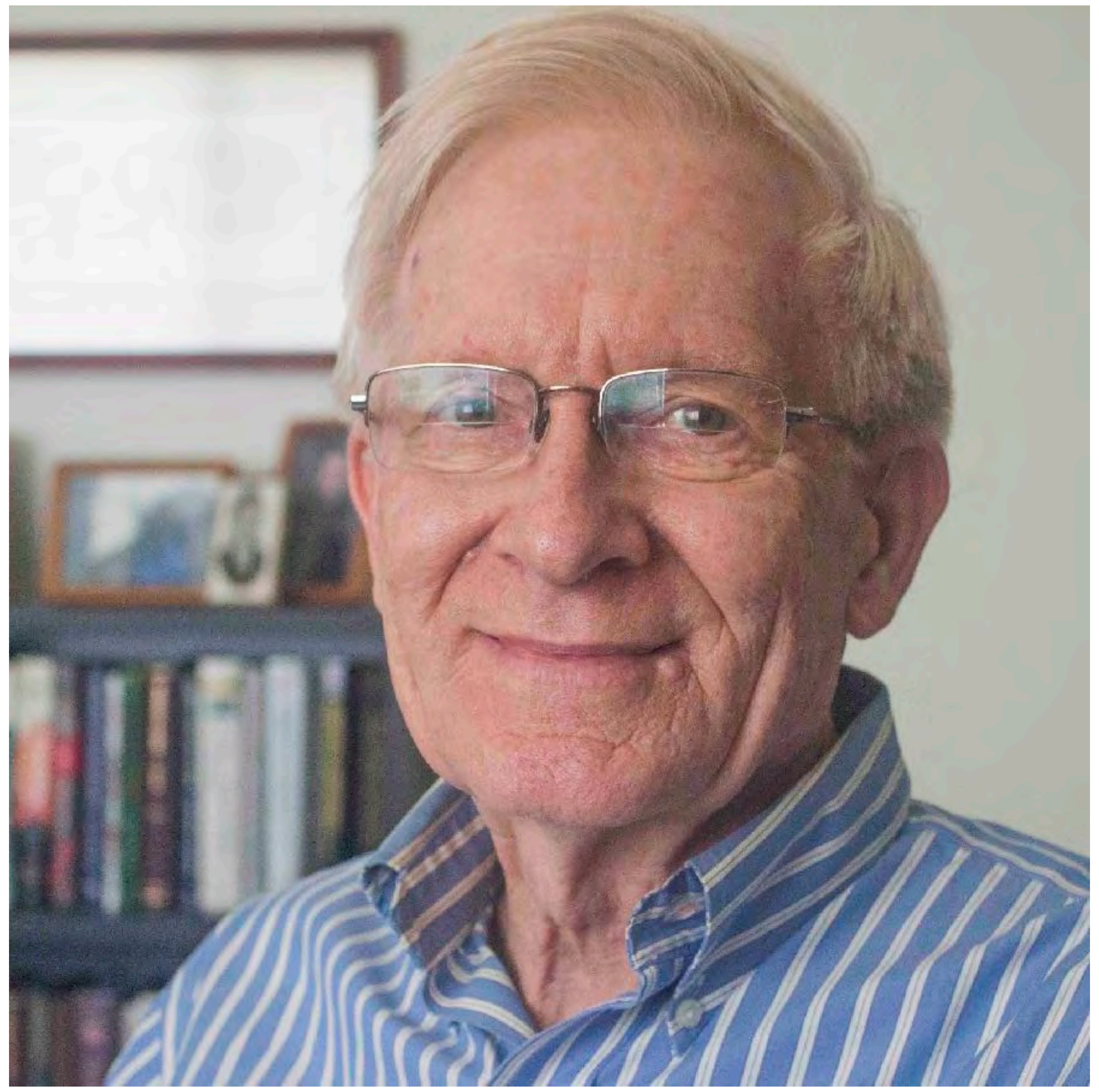

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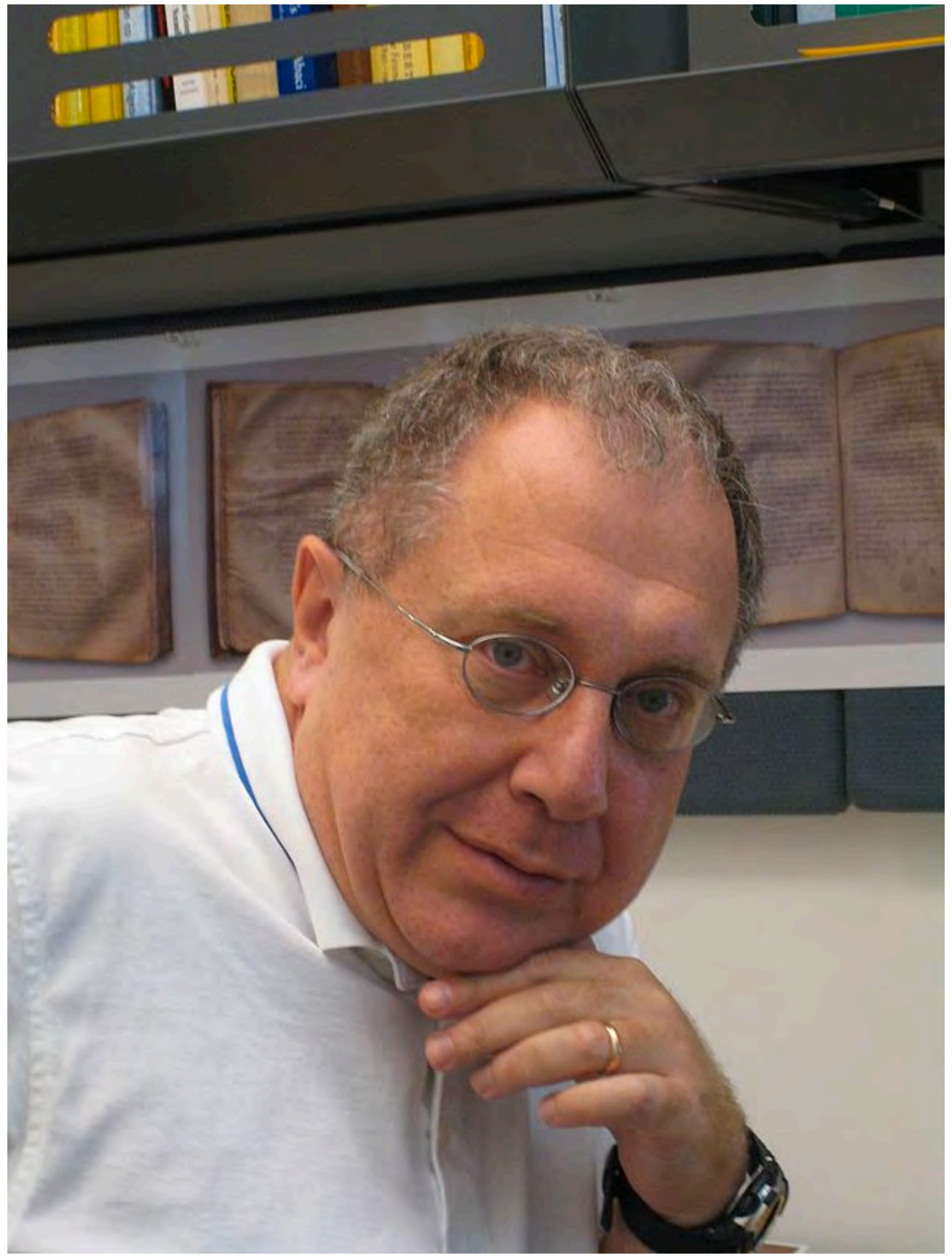

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1976-1987

1976 Parallel Computation and Associative Property

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1976 Parallel Computation and Associative Property

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Parallel reduction is associated with monoids

Software is associated with Algebraic Structures

1981 Tecton

The Tecton language

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TECTON: A LANGUAGE FOR MANIPULATING GENERIC OBJECTS

D. Kapur, D.R. Musser, and A.A. Stepanov

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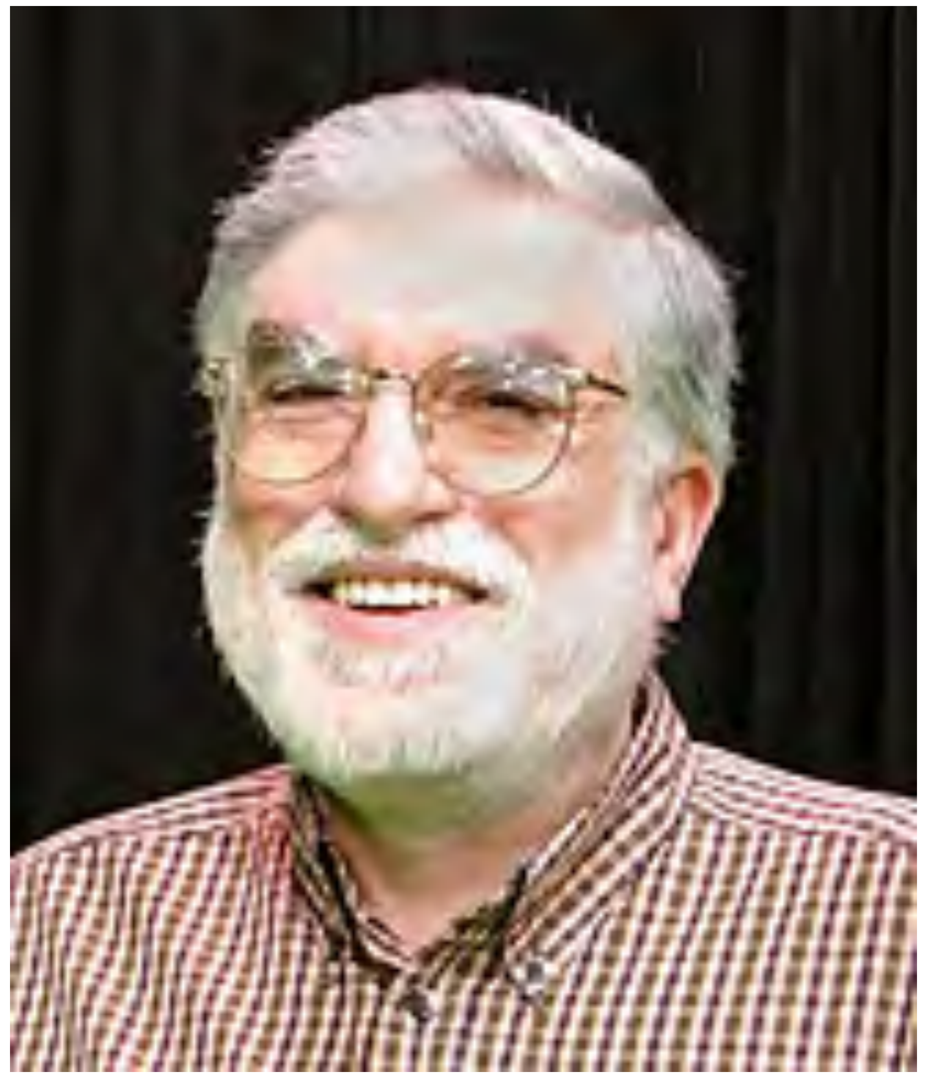

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Higher Order Programming

Higher Order Programming

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March 5, 1987

Polytechnic Institute of New York

USING TOURNAMENT TREES TO SORT

ALEXANDER STEPANOV AND AARON KERSHENBAUM

Polytechnic University
333 Jay Street
Brooklyn, New York 11201

Center for Advanced Technology
In Telecommunications

C.A.T.T. Technical Report 86-13

CENTER FOR
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CENTER FOR
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1987

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Alex works briefly at Bell Labs

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Starts a friendship with Bjarne Stroustrup

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Andrew Koenig explains the C machine

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Reads Ken Thompson's and Rob Pike's code for Unix and Plan 9

1987

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Leonhard Euler

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"De-Bourbakized"

1987

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“De-Bourbakized”

Nicolas Bourbaki

1987

Leonhard Euler

"De-Bourbakized"

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Knowledge is founded on the basis of precise, quantitative laws

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Mathematics is discovery, not invention

Software is defined on Algebraic Structures

1988

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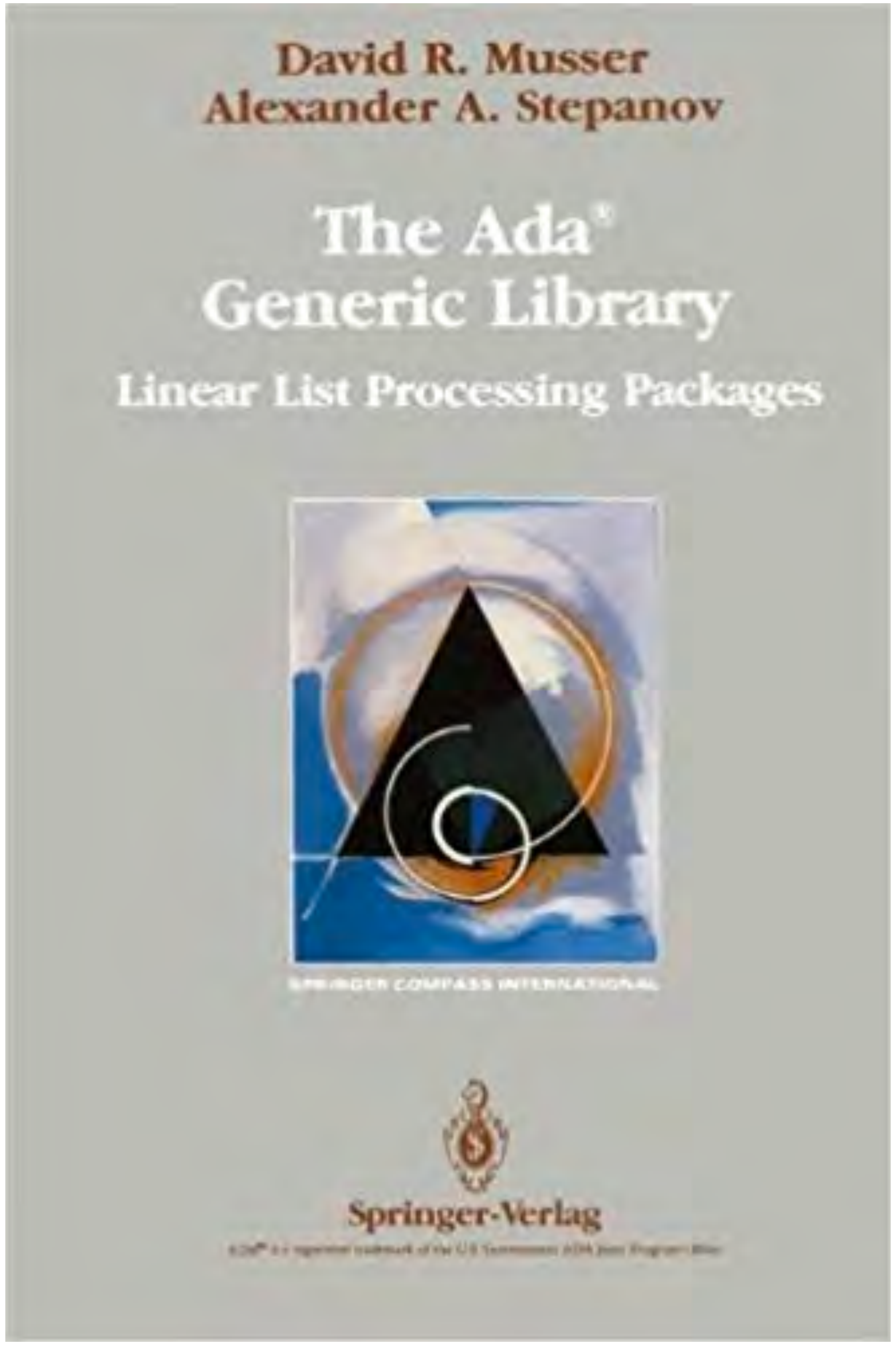
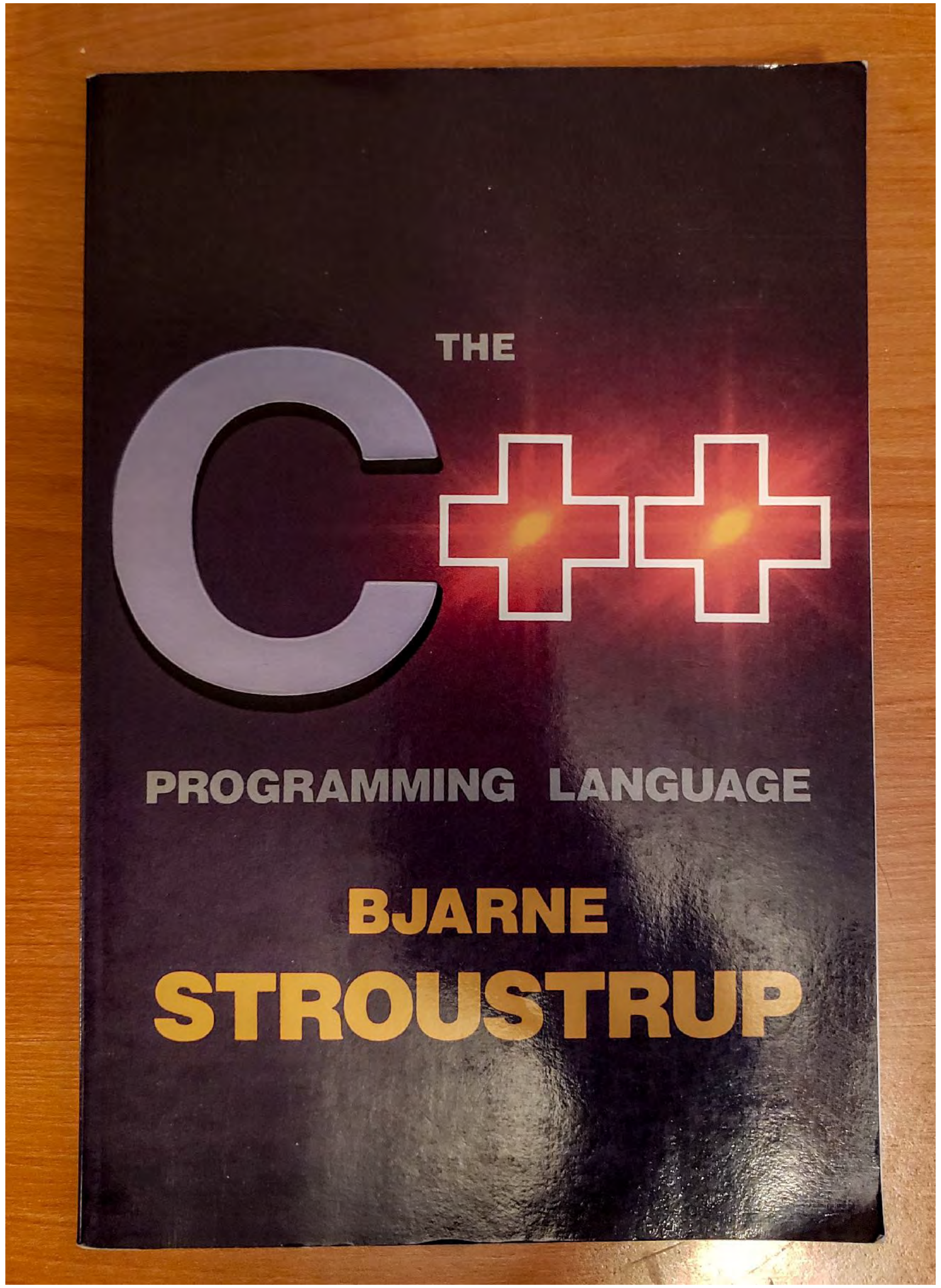
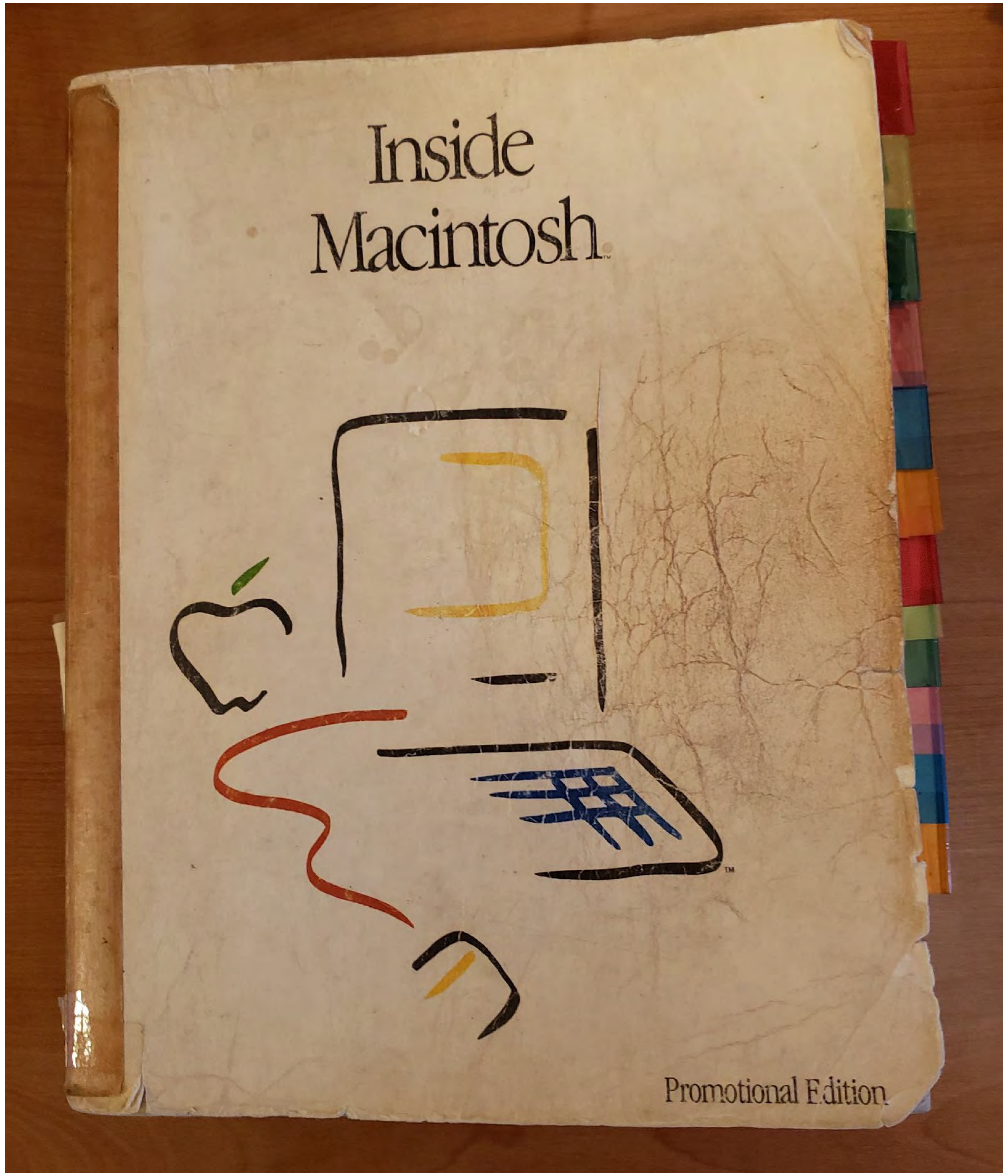
```
procedure Partition(S         : in out Sequence;
                    F, L      : in Coordinate;
                    Middle    : out Coordinate;
                    Middle_OK : out Boolean) is
  First : Coordinate := F;
  Last  : Coordinate := L;
begin
  loop
    loop
      if First = Last then
        Middle := First;
        Middle_OK := Test(S, First);
        return;
      end if;
      exit when not Test(S, First);
      First := Next(First);
    end loop;
    loop
      exit when Test(S, Last);
      Last := Prev(Last);
      if First = Last then
        Middle := First;
        Middle_OK := False;
        return;
      end if;
    end loop;
    Swap(S, First, Last);
    First := Next(First);
    if First = Last then
      Middle := First;
      Middle_OK := False;
      return;
    end if;
    Last := Prev(Last);
  end loop;
end Partition;
```

Figure 1: Body of Partition Algorithm


David R. Musser
Alexander A. Stepanov
The Ada®
Generic Library
Linear List Processing Packages
SPRINGER COMPASS INTERNATIONAL
Springer-Verlag


THE
C++
PROGRAMMING LANGUAGE
BJARNE
STROUSTRUP


Inside
Macintosh
Promotional Edition

```
TYPE QDByte    = -128..127;
     QDPtr     = ^QDByte;
     QDHandle  = ^QDPtr;
```

QuickDraw includes only the graphics and utility procedures and functions you'll need to create graphics on the screen. Keyboard input, mouse input, and larger user-interface constructs such as windows and menus are implemented in separate packages that use QuickDraw but are linked in as separate units. You don't need these units in order to use QuickDraw; however, you'll probably want to read the documentation for windows and menus and learn how to use them with your Macintosh programs.

THE MATHEMATICAL FOUNDATION OF QUICKDRAW

To create graphics that are both precise and pretty requires not supercharged features but a firm mathematical foundation for the features you have. If the mathematics that underlie a graphics package are imprecise or fuzzy, the graphics will be, too. QuickDraw defines some clear mathematical constructs that are widely used in its procedures, functions, and data types: the coordinate plane, the point, the rectangle, and the region.

The Coordinate Plane

All information about location, placement, or movement that you give to QuickDraw is in terms of coordinates on a plane. The coordinate plane is a two-dimensional grid, as illustrated in Figure 2.

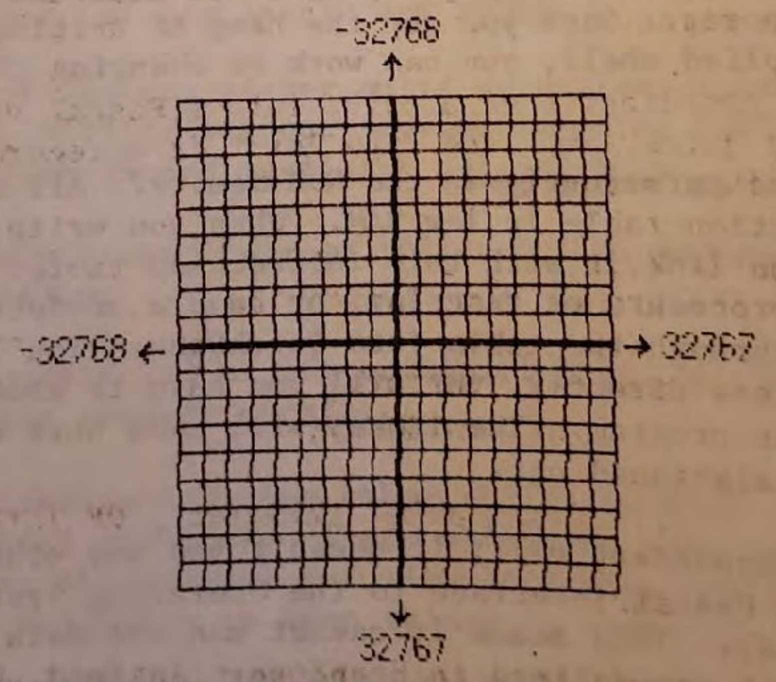


Figure 2. The Coordinate Plane

There are two distinctive features of the QuickDraw coordinate plane:

- All grid coordinates are integers.
- All grid lines are infinitely thin.

These concepts are important! First, they mean that the QuickDraw plane is finite, not infinite (although it's very large). Horizontal coordinates range from -32768 to +32767, and vertical coordinates have the same range. (An auxiliary package is available that maps real Cartesian space, with X, Y, and Z coordinates, onto QuickDraw's two-dimensional integer coordinate system.)

Second, they mean that all elements represented on the coordinate plane are mathematically pure. Mathematical calculations using integer arithmetic will produce intuitively correct results. If you keep in mind that grid lines are infinitely thin, you'll never have "endpoint paranoia" -- the confusion that results from not knowing whether that last dot is included in the line.

Points

On the coordinate plane are 4,294,967,296 unique points. Each point is at the intersection of a horizontal grid line and a vertical grid line. As the grid lines are infinitely thin, a point is infinitely small. Of course there are more points on this grid than there are dots on the Macintosh screen: when using QuickDraw you associate small parts of the grid with areas on the screen, so that you aren't bound into an arbitrary, limited coordinate system.

The coordinate origin (Ø,Ø) is in the middle of the grid. Horizontal coordinates increase as you move from left to right, and vertical coordinates increase as you move from top to bottom. This is the way both a TV screen and a page of English text are scanned: from the top left to the bottom right.

You can store the coordinates of a point into a Pascal variable whose type is defined by QuickDraw. The type Point is a record of two integers, and has this structure:

```
TYPE VHSelect = (V,H);
     Point    = RECORD CASE INTEGER OF

                  Ø:  (v:  INTEGER;
                       h:  INTEGER);

                  1:  (vh:  ARRAY [VHSelect] OF INTEGER)

                END;
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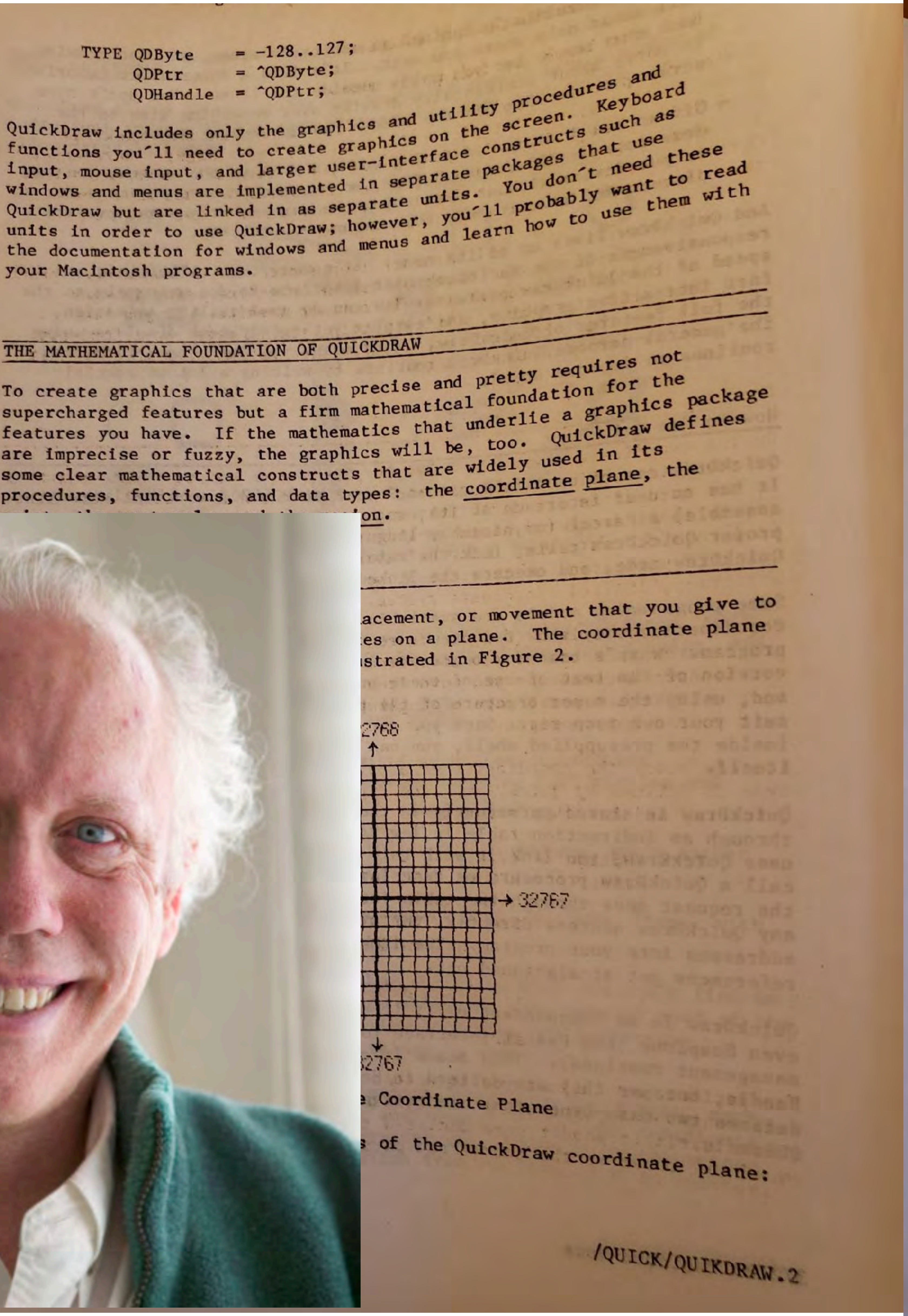
The variant part allows you to access the vertical and horizontal components of a point either individually or as an array. For example, if the variable goodPt were declared to be of type Point, the following would all refer to the coordinate parts of the point:



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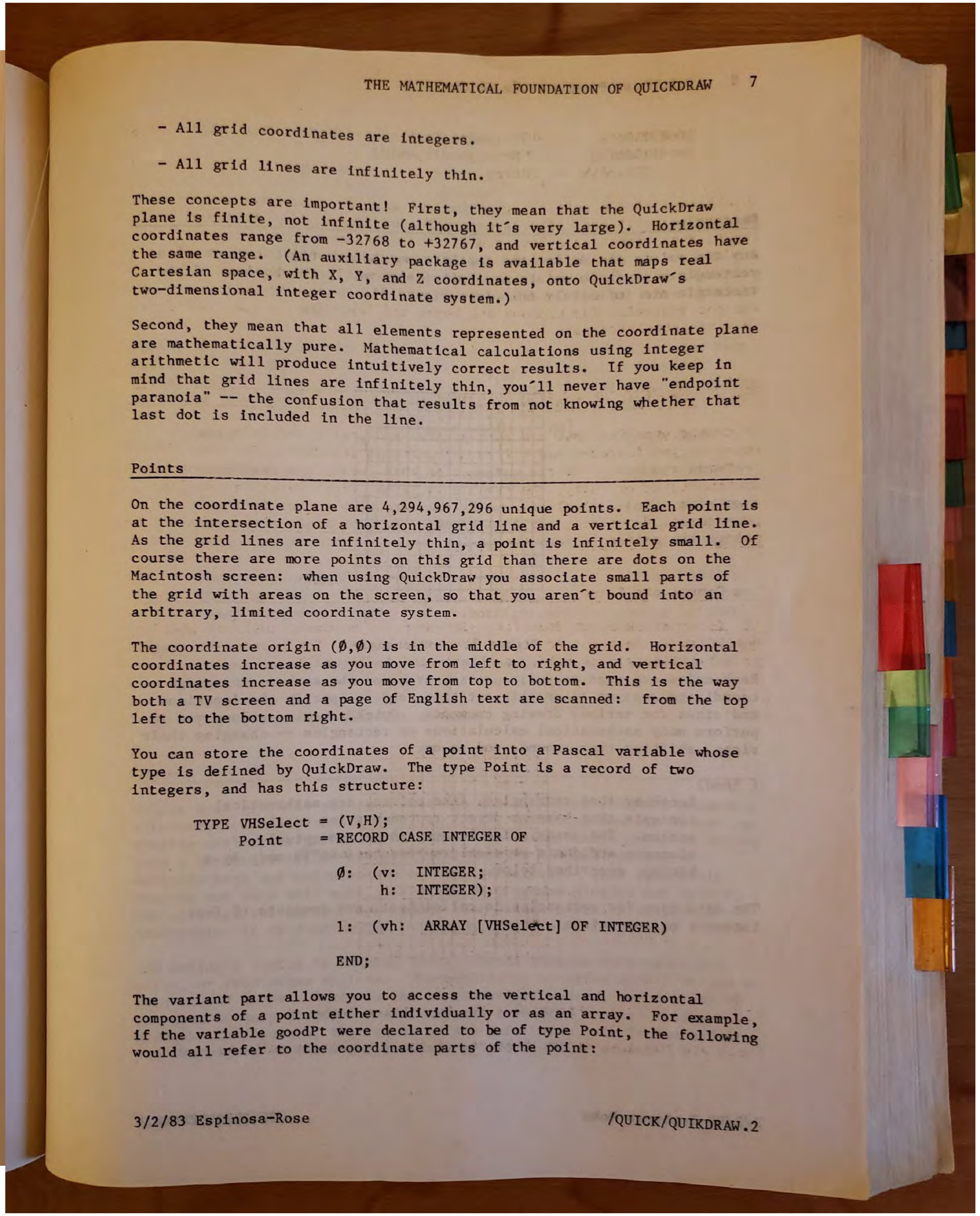
/QUICK/QUIKDRAW.2



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3/2/83 Espinosa-Rose /QUICK/QUIKDRAW.2

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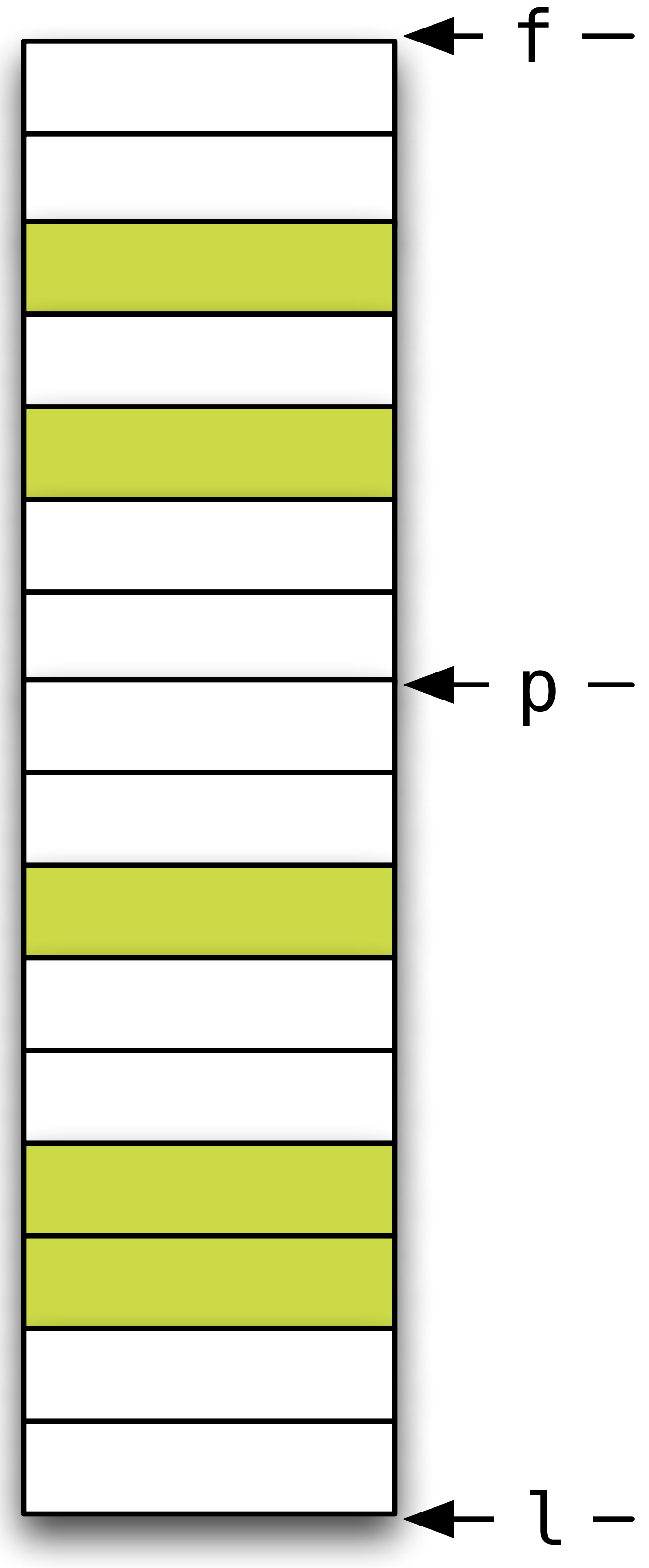
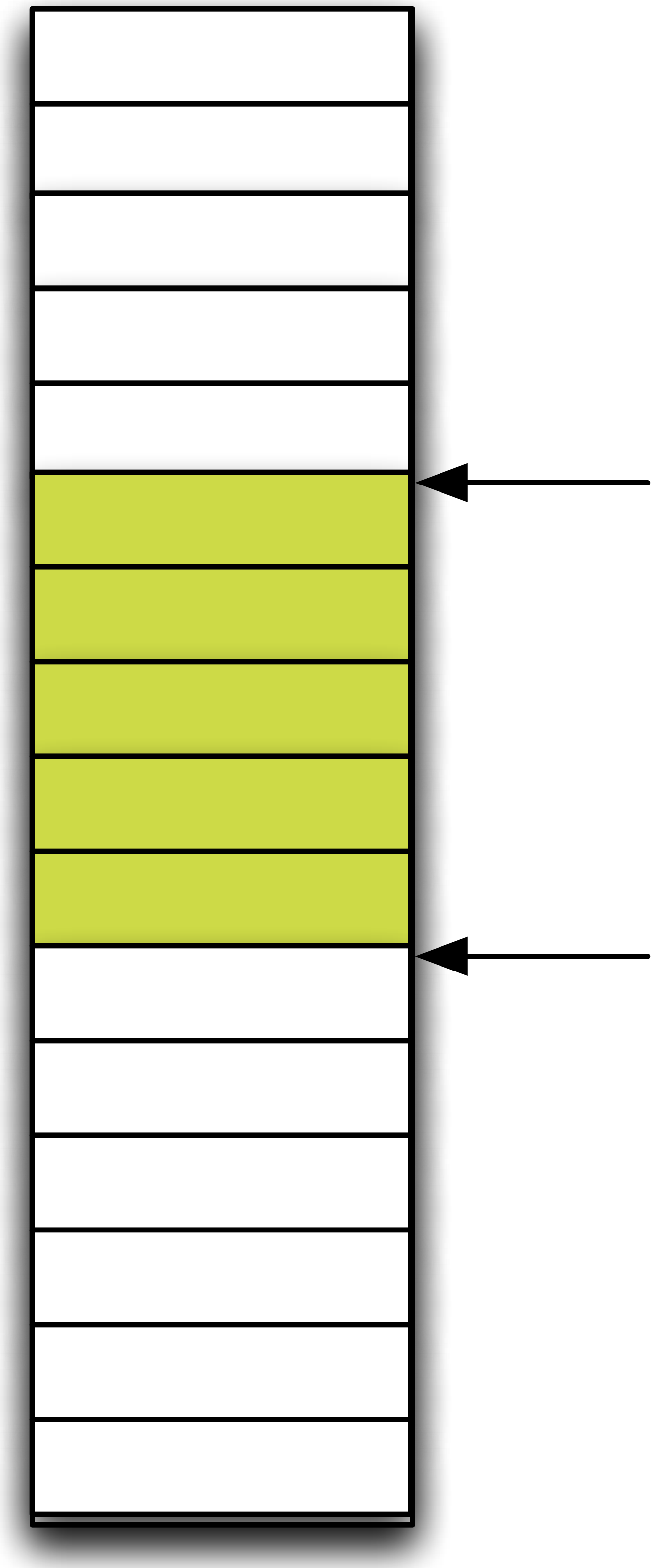
Gather




```
template <typename I, // I models BidirectionalIterator
          typename S> // S models UnaryPredicate
auto gather(I f, I l, I p, S s) -> pair<I, I>
{
    return { stable_partition(f, p, not1(s)),
             stable_partition(p, l, s) };
}
```

Gather



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For a sequence of *n* elements there are *n + 1* positions

1993

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Movie: Jurassic Park

Bombing of World Trade Center

Bill Clinton sworn in

Video Games: Doom and MYST

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Movie: Jurassic Park

Bombing of World Trade Center

Bill Clinton sworn in

Video Games: Doom and MYST

1993

Alex resumes work on Generic Programming

Andrew Koenig suggests writing a standard library proposal

1994

The Standard Template Library

Alexander Stepanov

Silicon Graphics Inc.
2011 N. Shoreline Blvd.
Mt. View, CA 94043
stepanov@mti.sgi.com

Meng Lee

Hewlett-Packard Laboratories
1501 Page Mill Road
Palo Alto, CA 94304
lee@hpl.hp.com

October 31, 1995

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Palo Alto, CA 94304
lee@hpl.hp.com

October 31, 1995

1983

programming pearls

By Jon Bentley

WRITING CORRECT PROGRAMS

In the late 1960s people were talking about the promise of programs that verify the correctness of other programs. Unfortunately, it is now the middle of the 1980s, and, with precious few exceptions, there is still little more than talk about automated verification systems. Despite unrealized expectations, however, the research on program verification has given us something far more valuable than a black box that gobbles programs and flashes "good" or "bad"—we now have a fundamental understanding of computer programming.

The purpose of this column is to show how that fundamental understanding can help programmers write correct programs. But before we get to the subject itself, we must keep it in perspective. Coding skill is just one small part of writing correct programs. The majority of the task is the subject of the three previous columns: problem definition, algorithm design, and data structure selection. If you perform those tasks well, then writing correct code is usually easy.

The Challenge of Binary Search

Even with the best of designs, every now and then a programmer has to write subtle code. This column is about one problem that requires particularly careful code: binary search. After defining the problem and sketching an algorithm to solve it, we'll use principles of program verification in several stages as we develop the program.

The problem is to determine whether the sorted array $X[1..N]$ contains the element T. Precisely, we know that $N \geq 0$ and that $X[1] \leq X[2] \leq \cdots \leq X[N]$. The types of T and the elements of X are the same; the pseudocode should work equally well for integers, reals or strings. The answer is stored in the integer P (for position); when P is zero T is not in $X[1..N]$, otherwise $1 \leq P \leq N$ and $T = X[P]$.

Binary search solves the problem by keeping track of a range within the array in which T must be if it is anywhere in the array. Initially, the range is the entire array. The range is diminished by comparing its middle element to T and discarding half the range. This process continues until T is discovered in the array or until the range in which it must lie is known to be empty. The process makes roughly $\log_2 N$ comparisons.

Most programmers think that with the above description in hand, writing the code is easy; they're wrong. The only way you'll believe this is by putting down this column right now, and writing the code yourself. Try it.

I've given this problem as an in-class assignment in courses at Bell Labs and IBM. The professional programmers had one hour (sometimes more) to convert the above description into a program in the language of their choice; a high-level pseudocode was fine. At the end of the specified time, almost all the programmers reported that they had correct code for the task. We would then take 30 minutes to examine their code, which the programmers did with test cases. In many different classes and with over a hundred programmers, the results varied little: 90 percent of the programmers found bugs in their code (and I wasn't always convinced of the correctness of the code in which no bugs were found).

I found this amazing: only about 10 percent of professional programmers were able to get this small program right. But they aren't the only ones to find this task difficult. In the history in Section 6.2.1 of his *Sorting and Searching*, Knuth points out that while the first binary search was published in 1946, the first published binary search without bugs did not appear until 1962.

Writing The Program

The key idea of binary search is that we always know that if T is anywhere in $X[1..N]$, then it must be in a certain range of X. We'll use the shorthand *MustBe(range)* to mean that if T is anywhere in the array, then it must be in *range*. With this notation, it's easy to convert the above description of binary search into a program sketch.

```
initialize range to designate X[1..N]
loop
    { invariant: MustBe(range) }
    if range is empty,
        return that T is nowhere in the
        array
    compute M, the middle of the range
    use M as a probe to shrink the range
        if T is found during the
        shrinking process, return its
        position
  endloop
```

The crucial part of this program is the *loop invariant*, which is enclosed in {}'s. This is an *assertion* about the program state that is invariantly true at the beginning and end of each iteration of the loop (hence its name); it formalizes the intuitive notion we had above.

We'll now refine the program, making sure that all our actions respect the invariant. The first issue we must face is the representation of *range*: we'll use two indices L and U (for "lower" and "upper") to represent the range $L..U$. (There are other possible representations for a range, such as its begin-

programming pearls

By Jon Bentley

WRITING CORRECT PROGRAMS

In the late 1960s people were talking about the promise of programs that verify the correctness of other programs. Unfortunately, it is now the middle of the 1980s, and, with precious few exceptions, there is still little more than talk about automated verification systems. Despite unrealized expectations, however, the research on program verification has given us something far more valuable than a black box that gobbles programs and flashes "good" or "bad"—we now have a fundamental understanding of computer programming.

The purpose of this column is to show how that fundamental understanding can help programmers write correct programs. But before we get to the subject itself, we must keep it in perspective. Coding skill is just one small part of writing correct programs. The majority of the task is the subject of the three previous columns: problem definition, algorithm design, and data structure selection. If you perform those tasks well, then writing correct code is usually easy.

The Challenge of Binary Search

Even with the best of designs, every now and then a programmer has to write subtle code. This column is about one problem that requires particularly careful code: binary search. After defining the problem and sketching an algorithm to solve it, we'll use principles of program verification in several stages as we develop the program.

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– Jon Bentley, Programming Pearls

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Jon Bentley's Solution (translated to C++)

```
int binary_search(int x[], int n, int v) {
    int l = 0;
    int u = n - 1;

    while (true) {
        if (l > u) return -1;

        int m = (l + u) / 2;

        if (x[m] < v) l = m + 1;
        else if (x[m] == v) return m;
        else /* (x[m] > v) */ u = m - 1;
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STL implementation

```
template <class I, // I models ForwardIterator
          class T> // T is value_type(I)
I lower_bound(I f, I l, const T& v) {
    while (f != l) {
        auto m = next(f, distance(f, l) / 2);

        if (*m < v) f = next(m);
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1998

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Exception-Safety in Generic Components

Lessons Learned from Specifying Exception-Safety for the C++ Standard Library

David Abrahams

Dragon Systems
David_Abrahams@dragonsys.com

Abstract. This paper represents the knowledge accumulated in response to a real-world need: that the C++ Standard Template Library exhibit useful and well-defined interactions with exceptions, the error-handling mechanism built-in to the core C++ language. It explores the meaning of exception-safety, reveals surprising myths about exceptions and genericity, describes valuable tools for reasoning about program correctness, and outlines an automated testing procedure for verifying exception-safety.

Keywords: exception-safety, exceptions, STL, C++

1 What Is Exception-Safety?

Informally, exception-safety in a component means that it exhibits reasonable behavior when an exception is thrown during its execution. For most people, the term "reasonable" includes all the usual expectations for error-handling: that resources should not be leaked, and that the program should remain in a well-defined state so that execution can continue. For most components, it also includes the expectation that when an error is encountered, it is reported to the caller.

More formally, we can describe a component as minimally exception-safe if, when exceptions are thrown from within that component, its invariants are intact. Later on we'll see that at least three different levels of exception-safety can be usefully distinguished. These distinctions can help us to describe and reason about the behavior of large systems.

In a generic component, we usually have an additional expectation of *exception-neutrality*, which means that exceptions thrown by a component's type parameters should be propagated, unchanged, to the component's caller.

2 Myths and Superstitions

Exception-safety seems straightforward so far: it doesn't constitute anything more than we'd expect from code using more traditional error-handling techniques. It might be worthwhile, however, to examine the term from a psychological viewpoint. Nobody ever spoke of "error-safety" before C++ had exceptions.

M. Jazayeri, R. Loos, D. Musser (Eds.): Generic Programming '98, LNCS 1766, pp. 69–79, 2000.

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Fundamentals of Generic Programming

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Keywords: Generic programming, operator semantics, concept, regular type.

Abstract. Generic programming depends on the decomposition of programs into components which may be developed separately and combined arbitrarily, subject only to well-defined interfaces. Among the interfaces of interest, indeed the most pervasively and unconsciously used, are the fundamental operators common to all C++ built-in types, as extended to user-defined types, e.g. copy constructors, assignment, and equality. We investigate the relations which must hold among these operators to preserve consistency with their semantics for the built-in types and with the expectations of programmers. We can produce an axiomatization of these operators which yields the required consistency with built-in types, matches the intuitive expectations of programmers, and also reflects our underlying mathematical expectations.

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"We call the set of axioms satisfied by a data type and a set of operations on it a *concept*."

“We call the set of axioms satisfied by a data type and a set of operations on it a *concept*.”

"Since we wish to extend semantics as well as syntax from built-in types to user types, we introduce the idea of a *regular type*, which matches the built-in type semantics, thereby making our user-defined types behave like built-in types as well."

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NOTES ON THE FOUNDATIONS OF PROGRAMMING

ALEX STEPANOV AND MAT MARCUS

Disclaimer: Please do not redistribute. Instead, requests for a current draft should go to Mat Marcus. These notes are a work in progress and do not constitute a book. In particular, most of the current effort is directed towards writing up new material. As a consequence little time remains for structuring, refinement, or clean up, so please be patient. Nevertheless, suggestions, comments and corrections are welcomed. Please reply to mmarcus@adobe.com and stepanov@adobe.com.

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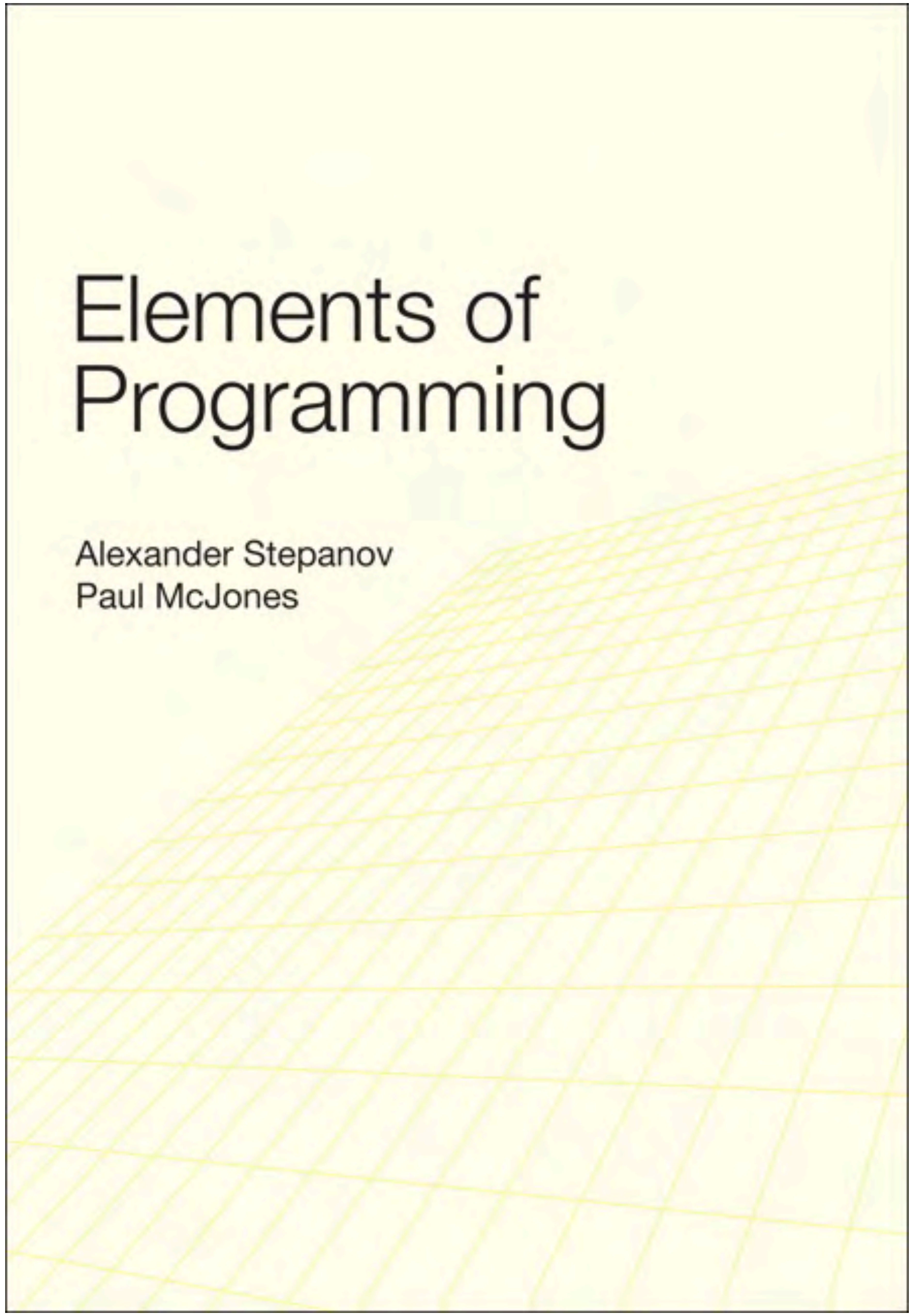
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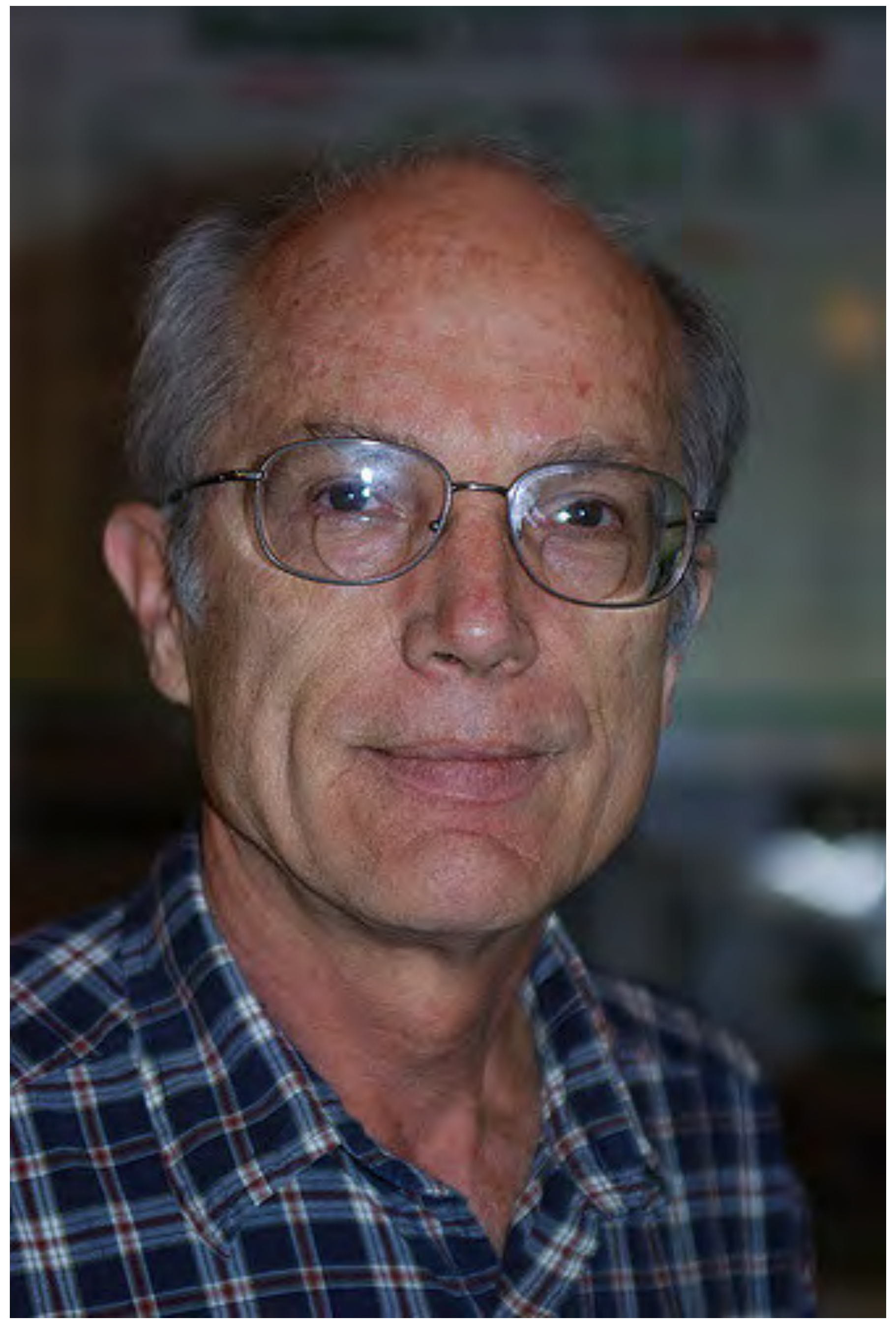

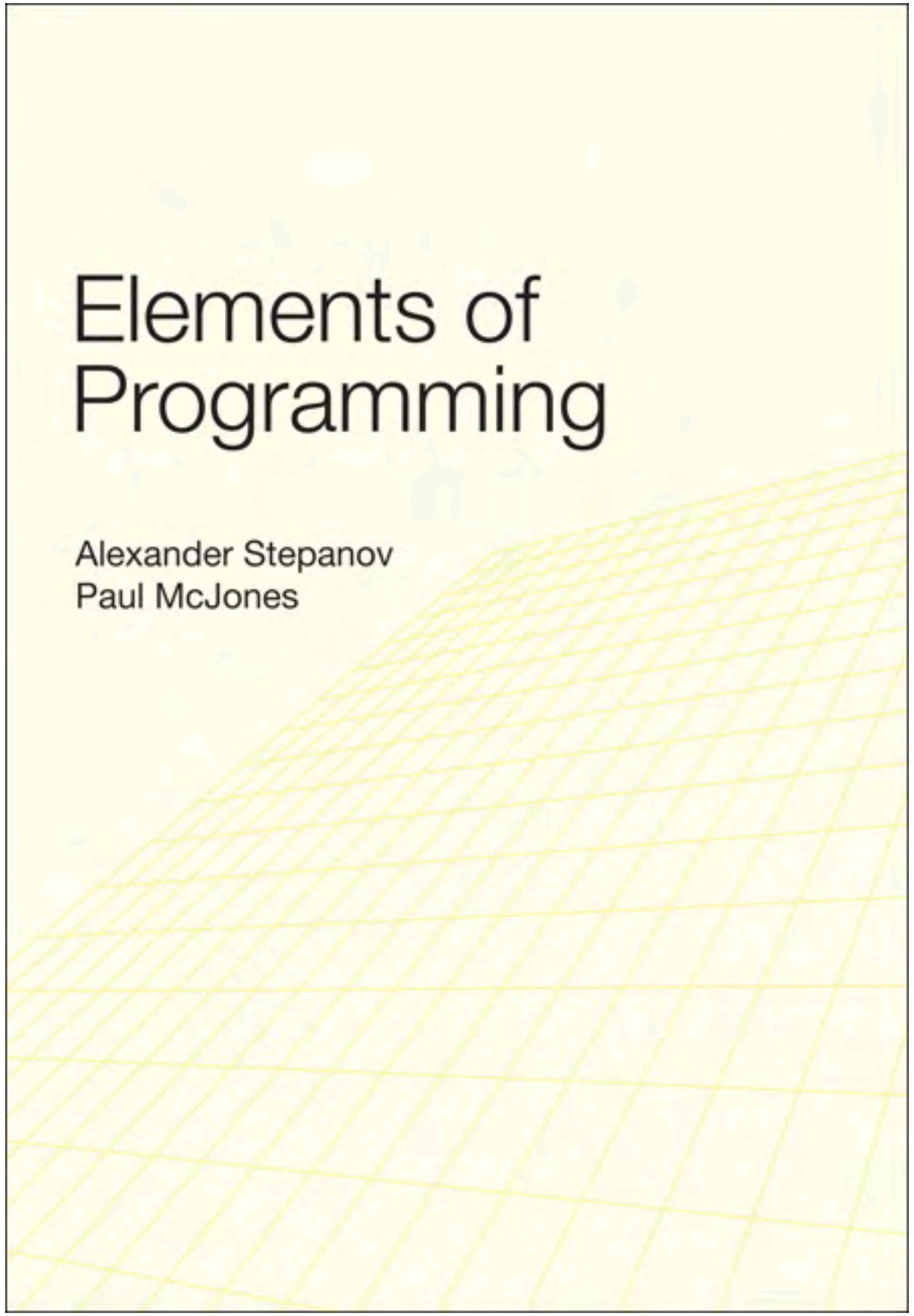
Elements of Programming
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Paul McJones

```
template <typename I, typename P>
    requires(Mutable(I) && ForwardIterator(I) &&
        UnaryPredicate(P) && ValueType(I) == Domain(P))
I partition_semistable(I f, I l, P p) {
    // Precondition: mutable_bounded_range(f, l)
    I i = find_if(f, l, p);
    if (i == l) return i;
    I j = successor(i);
    while (true) {
        j = find_if_not(j, l, p);
        if (j == l) return i;
        swap_step(i, j);
    }
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Appendix B. Programming Language

Sean Parent and Bjarne Stroustrup

This appendix defines the subset of C++ used in the book. To simplify the syntax, we use a few library facilities as intrinsics. These intrinsics are not written in this subset but take advantage of other C++ features. Section B.1 defines this subset; Section B.2 specifies the implementation of the intrinsics.

B.1 Language Definition

Syntax Notation

An Extended Backus-Naur Form designed by Niklaus Wirth is used. Wirth [1977, pages 822–823] describes it as follows:

> The word *identifier* is used to denote *nonterminal symbol*, and *literal* stands for *terminal symbol*. For brevity, *identifier* and *character* are not defined in further detail.

```
syntax     = {production}.
production = identifier "=" expression ".".
expression = term {"|" term}.
term       = factor {factor}.
factor     = identifier | literal
               | "(" expression ")"
               | "[" expression "]"
               | "{" expression "}".
literal    = """" character {character} """".
```

> Repetition is denoted by curly brackets, i.e., {a} stands for ∈ |a|aa|aaa |.... Optionality is expressed by square brackets, i.e., [a] stands for a | ∈ . Parentheses merely serve for grouping, e.g., (a|b)c stands for ac|bc. Terminal symbols, i.e., literals, are enclosed in quote marks (and, if a quote mark appears as a literal itself, it is written twice).

Lexical Conventions

The following productions give the syntax for identifiers and literals:

The while statement repeatedly evaluates the expression and executes the statement as long as the expression is true. The do statement repeatedly executes the statement and evaluates the expression until the expression is false. In either case, the expression must evaluate to a Boolean.

The compound statement executes the sequence of statements in order.

The goto statement transfers execution to the statement following the corresponding label in the current function.

The break statement terminates the execution of the smallest enclosing switch, while, or do statement; execution continues with the statement following the terminated statement.

The typedef statement defines an alias for a type.

Templates

A template allows a structure or procedure to be parameterized by one or more types or constants. Template definitions and template names use < and > as delimiters.[2]

> [2] To disambiguate between the use of < and > as relations or as template name delimiters, once a structure_name or procedure_name is parsed as part of a template, it becomes a terminal symbol.

```
template       = template_decl
                   (structure | procedure | specialization).
specialization = "struct" structure_name "<" additive_list ">"
                   [structure_body] ";".
template_decl  = "template" "<" [parameter_list] ">" [constraint].
constraint     = "requires" "(" expression ")".

template_name  = (structure_name | procedure_name)
                   ["<" additive_list ">"].
additive_list  = additive ("," additive).
```

When a template_name is used as a primary, the template definition is used to generate a structure or procedure with template parameters replaced by corresponding template arguments. These template arguments are either given explicitly as the delimited expression list in the template_name or, for procedures, may be deduced from the procedure argument types.

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This concept describes a homogeneous functional procedure:

$$
\begin{aligned}
&\mathit{HomogeneousFunction}(\mathsf{F}) \triangleq \\
&\quad \mathit{FunctionalProcedure}(\mathsf{F}) \\
&\wedge\ \mathsf{Arity}(\mathsf{F}) > 0 \\
&\wedge\ (\forall \mathsf{i}, \mathsf{j} \in \mathbb{N})(\mathsf{i}, \mathsf{j} < \mathsf{Arity}(\mathsf{F})) \Rightarrow (\mathsf{InputType}(\mathsf{F}, \mathsf{i}) = \mathsf{InputType}(\mathsf{F}, \mathsf{j})) \\
&\wedge\ \mathsf{Domain} : \mathit{HomogeneousFunction} \to \mathit{Regular} \\
&\qquad \mathsf{F} \mapsto \mathsf{InputType}(\mathsf{F}, 0)
\end{aligned}
$$

2006

Concepts: Linguistic Support for Generic Programming in C++

Douglas Gregor
Indiana University
dgregor@osl.iu.edu

Jaakko Järvi
Texas A&M University
jarvi@cs.tamu.edu

Jeremy Siek
Rice University
Jeremy.G.Siek@rice.edu

Bjarne Stroustrup
Texas A&M University
bs@cs.tamu.edu

Gabriel Dos Reis
Texas A&M University
gdr@cs.tamu.edu

Andrew Lumsdaine
Indiana University
lums@osl.iu.edu

Abstract

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Adobe

Concepts: Linguistic Support for Generic Programming in C++

Douglas Gregor
Indiana University
dgregor@osl.iu.edu

Jaakko Järvi
Texas A&M University
jarvi@cs.tamu.edu

Jeremy Siek
Rice University
Jeremy.G.Siek@rice.edu

Bjarne Stroustrup
Texas A&M University
bs@cs.tamu.edu

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dgregor@osl.iu.edu

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2011

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2012

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Date: 2012-01-13
Working group: Evolution
Reply to: Bjarne Stroustrup <bs@cs.tamu.edu>
Andrew Sutton <asutton@cs.tamu.edu>

A Concept Design for the STL

B. Stroustrup and A. Sutton (Editors)

Jan, 2012

Participants:
Ryan Ernst, A9.com, Inc.
Anil Gangolli, A9.com, Inc.
Jon Kalb, A9.com, Inc.
Andrew Lumsdaine, Indiana University (Aug. 1-4)
Paul McJones, independent
Sean Parent, Adobe Systems Incorporated (Aug. 1-3)
Dan Rose, A9.com, Inc.
Alex Stepanov, A9.com, Inc.
Bjarne Stroustrup, Texas A&M University (Aug. 1-3)
Andrew Sutton, Texas A&M University
Larisse Voufo [†], Indiana University
Jeremiah Willcock, Indiana University
Marcin Zalewski [†], Indiana University

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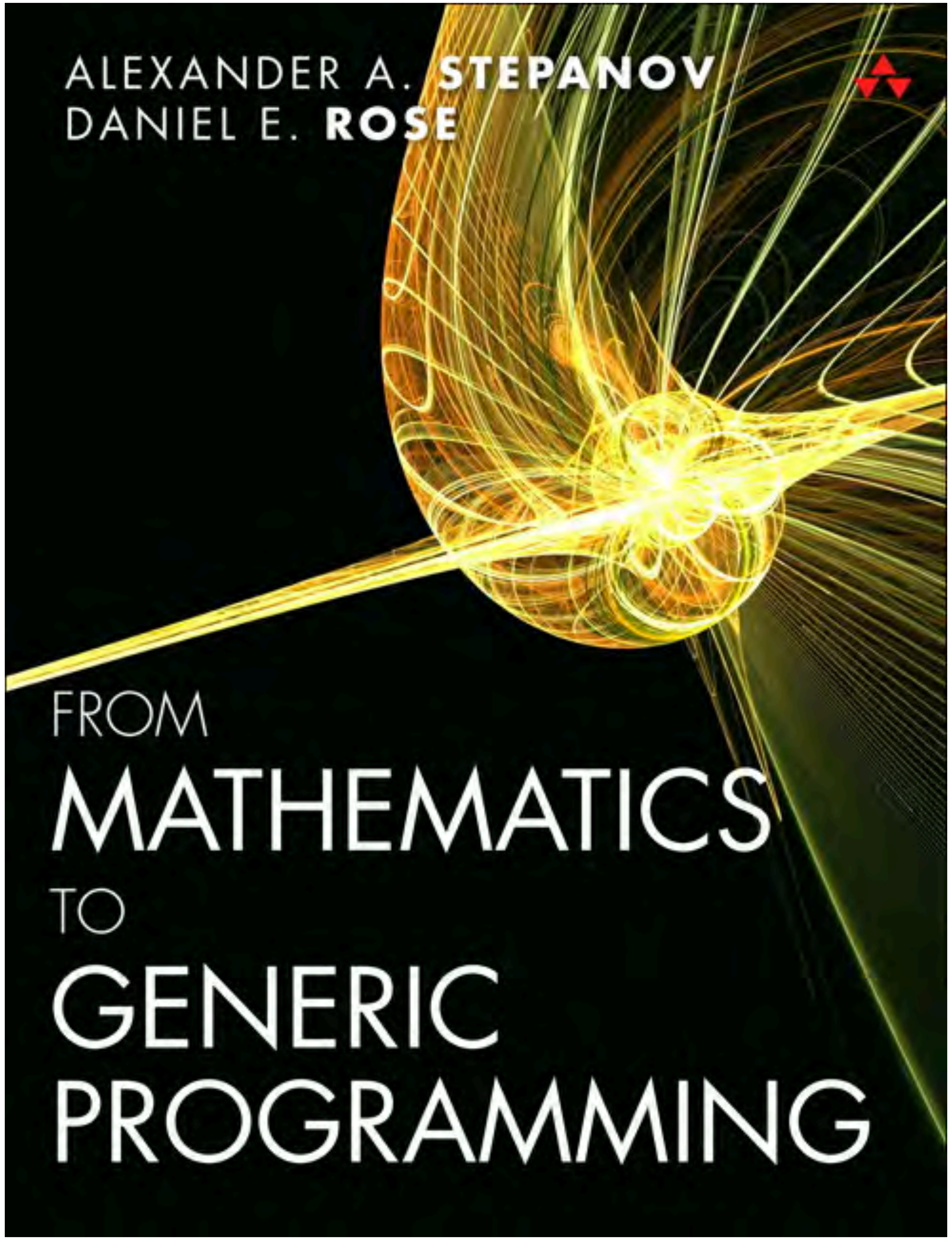
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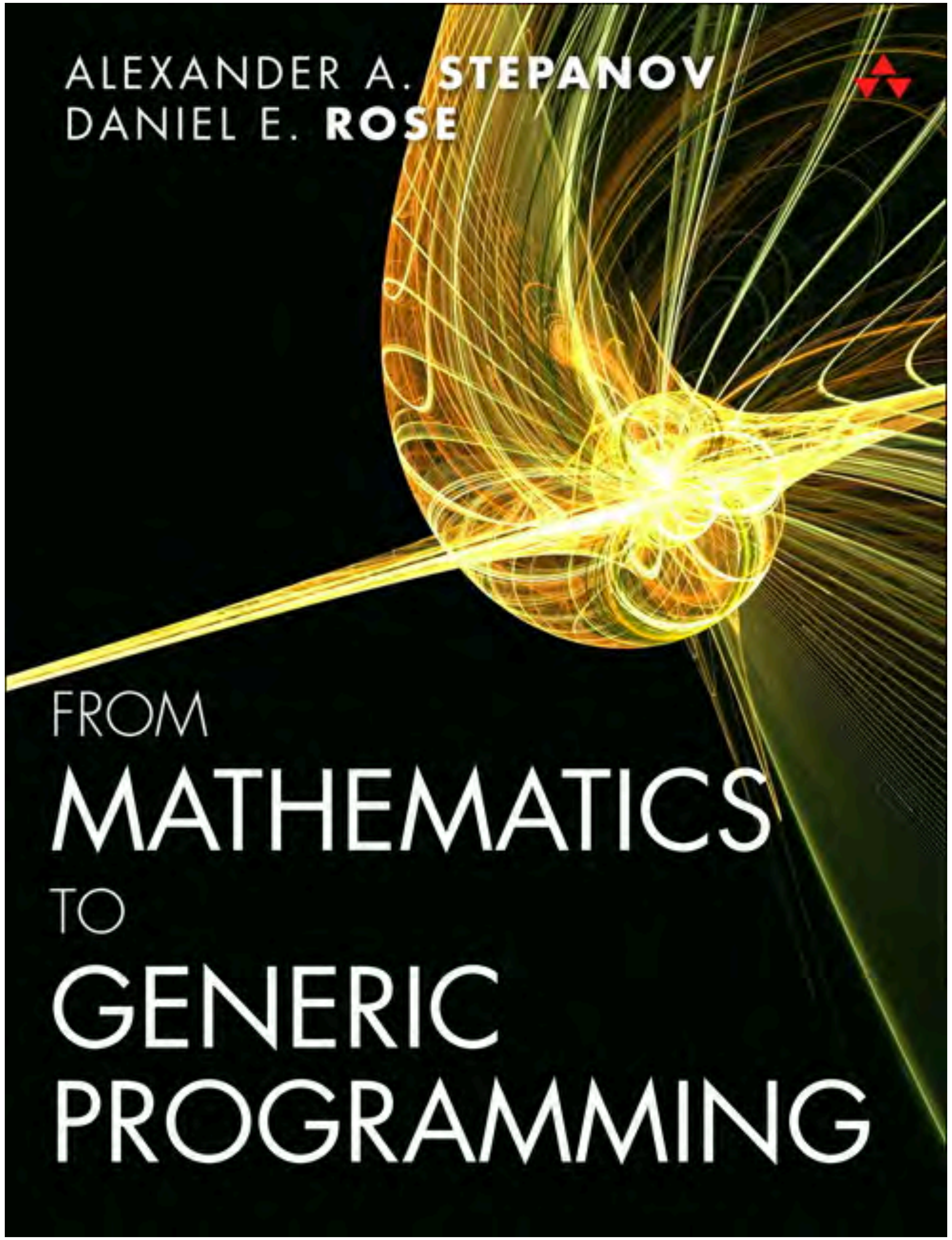
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TO
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2016

2020

17 Templates [temp]

1 A *template* defines a family of classes, functions, or variables, an alias for a family of types, or a concept.

template-declaration:
  template-head declaration
  template-head concept-definition

template-head:
  `template` `<` *template-parameter-list* `>` *requires-clause*$_{opt}$

template-parameter-list:
  template-parameter
  template-parameter-list `,` *template-parameter*

requires-clause:
  `requires` *constraint-logical-or-expression*

constraint-logical-or-expression:
  constraint-logical-and-expression
  constraint-logical-or-expression `||` *constraint-logical-and-expression*

constraint-logical-and-expression:
  primary-expression
  constraint-logical-and-expression `&&` *primary-expression*

concept-definition:
  `concept` *concept-name* `=` *constraint-expression* `;`

concept-name:
  identifier

[*Note:* The `>` token following the *template-parameter-list* of a *template-declaration* may be the product of replacing a `>>` token by two consecutive `>` tokens (17.2). — *end note*]

2 The *declaration* in a *template-declaration* (if any) shall

(2.1) — declare or define a function, a class, or a variable, or

(2.2) — define a member function, a member class, a member enumeration, or a static data member of a class template or of a class nested within a class template, or

(2.3) — define a member template of a class or class template, or

(2.4) — be a *deduction-guide*, or

(2.5) — be an *alias-declaration*.

3 A *template-declaration* is a *declaration*. A *template-declaration* is also a definition if its *template-head* is followed by either a *concept-definition* or a *declaration* that defines a function, a class, a variable, or a static data member. A declaration introduced by a template declaration of a variable is a *variable template*. A variable template at class scope is a *static data member template*.

[*Example:*

```
template<class T>
  constexpr T pi = T(3.1415926535897932385L);
template<class T>
  T circular_area(T r) {
    return pi<T> * r * r;
  }
struct matrix_constants {
  template<class T>
    using pauli = hermitian_matrix<T, 2>;
  template<class T>
    constexpr pauli<T> sigma1 = { { 0, 1 }, { 1, 0 } };
  template<class T>
    constexpr pauli<T> sigma2 = { { 0, -1i }, { 1i, 0 } };
```


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17 Templates [temp]

requires-clause:
    requires *constraint-logical-or-expression*

constraint-logical-or-expression:
    constraint-logical-and-expression
    constraint-logical-or-expression `||` *constraint-logical-and-expression*

constraint-logical-and-expression:
    primary-expression
    constraint-logical-and-expression `&&` *primary-expression*

concept-definition:
    concept *concept-name* `=` *constraint-expression* `;`

concept-name:
    identifier

```
  constexpr pauli<T> sigma1 = { { 0, 1 }, { 1, 0 } };
template<class T>
  constexpr pauli<T> sigma2 = { { 0, -1i }, { 1i, 0 } };
```

“Generic programming is about abstracting and classifying algorithms and data structures.

It gets its inspiration from Knuth and not from type theory.

Its goal is the incremental construction of systematic catalogs of useful, efficient and abstract algorithms and data structures.

Such an undertaking is still a dream."

– Alex Stepanov

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References

Much of the material in this talk can be found at

http://stepanovpapers.com/

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Sincere apologies to anyone I left out, your contribution was important.