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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



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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David R. Musser<sup>†</sup>

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Alexander A. Stepanov

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Post Office Box 10490  
Palo Alto, California 94303-0969

## Abstract

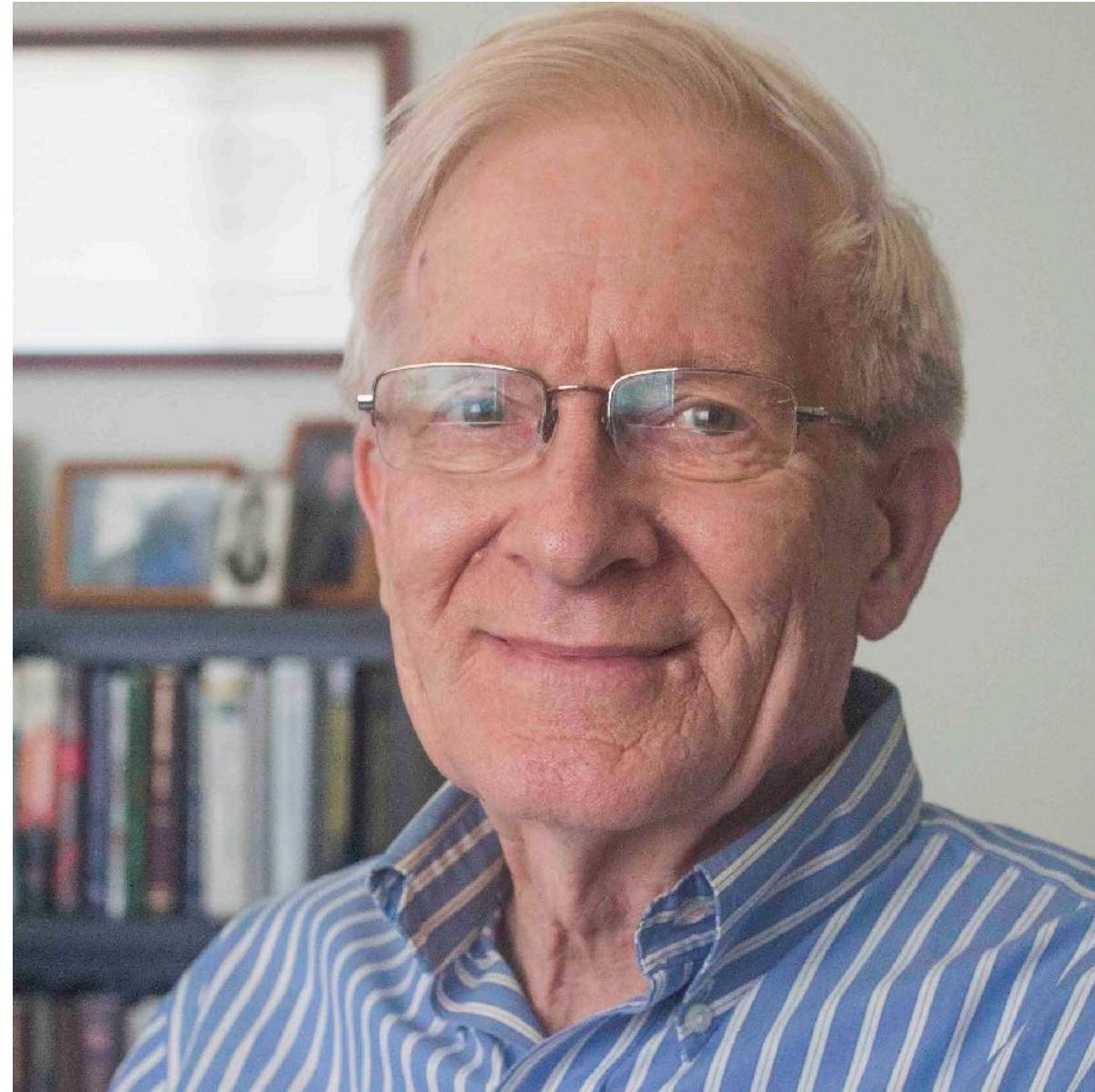
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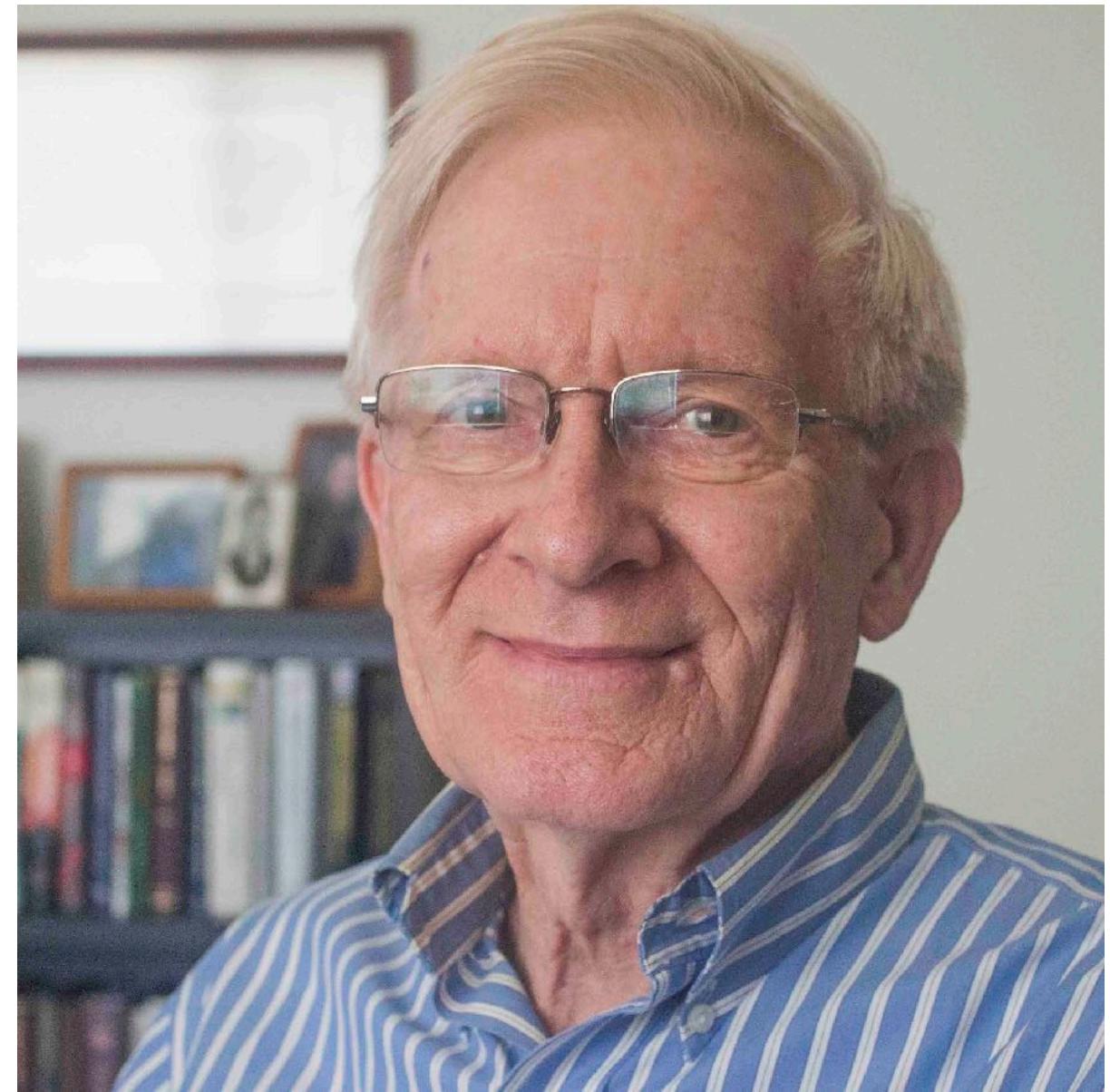
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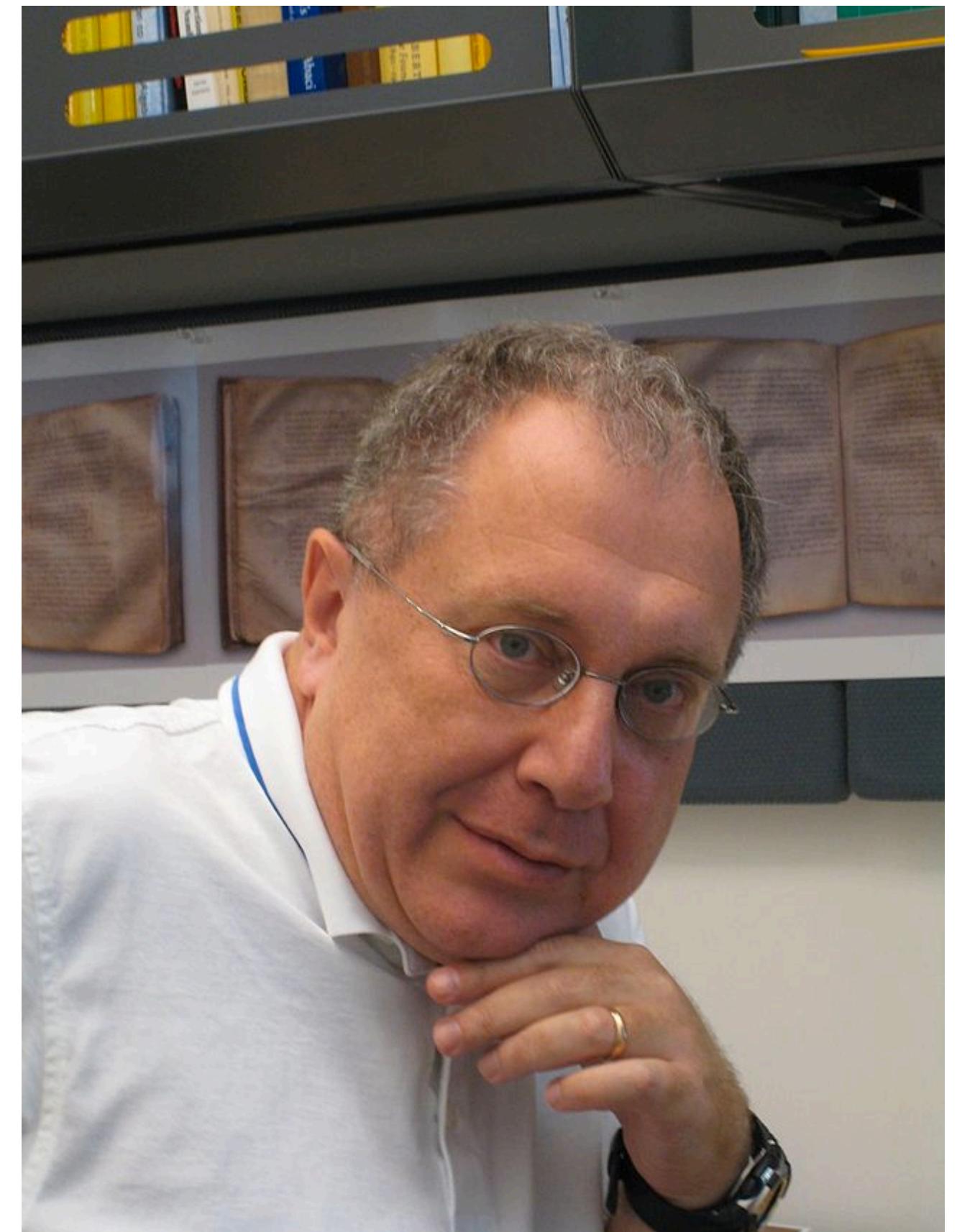
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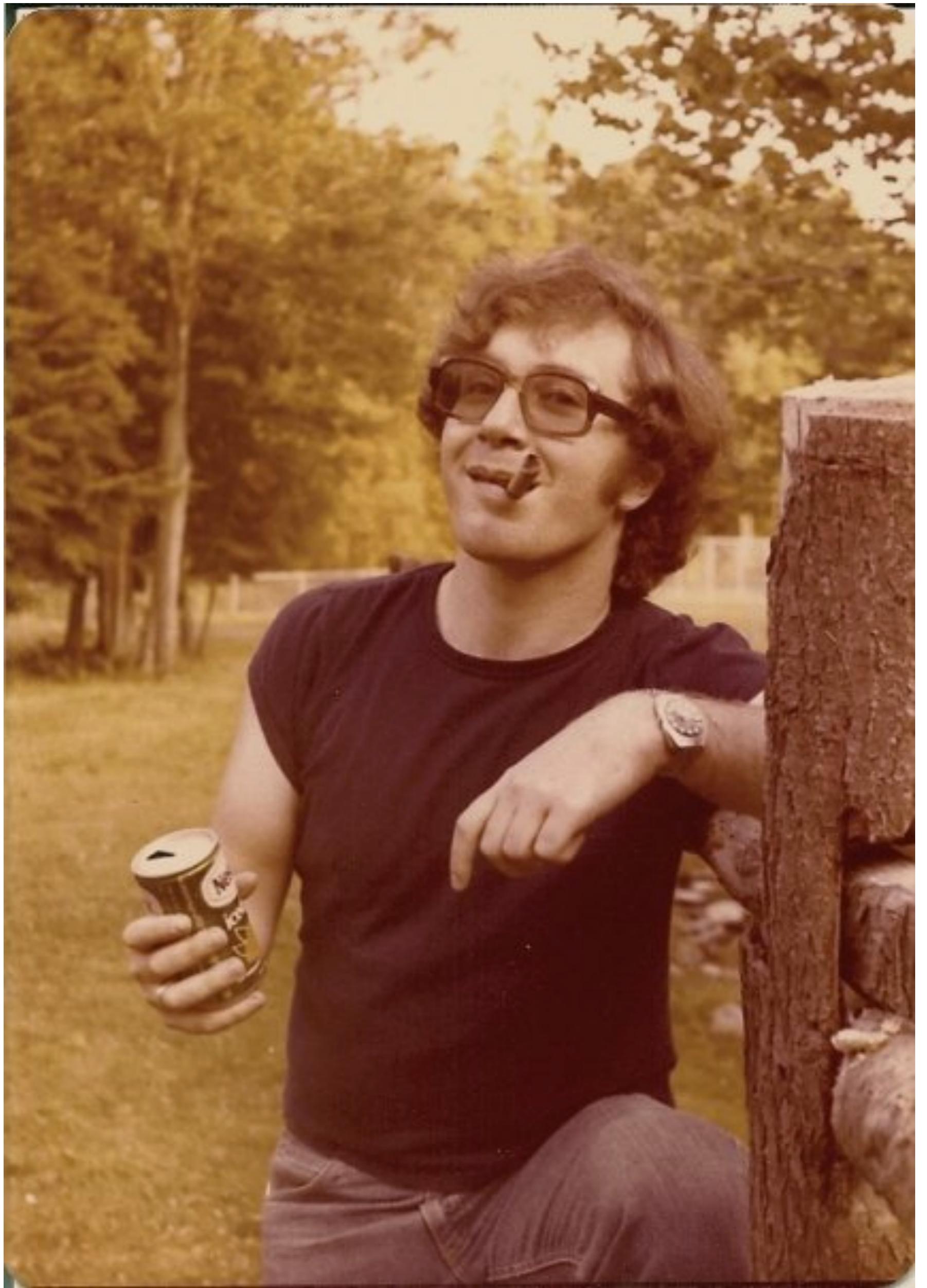
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1976-1987



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A binary operation  $\bullet$  on a set  $S$  is called *associative* if it satisfies the associative law:

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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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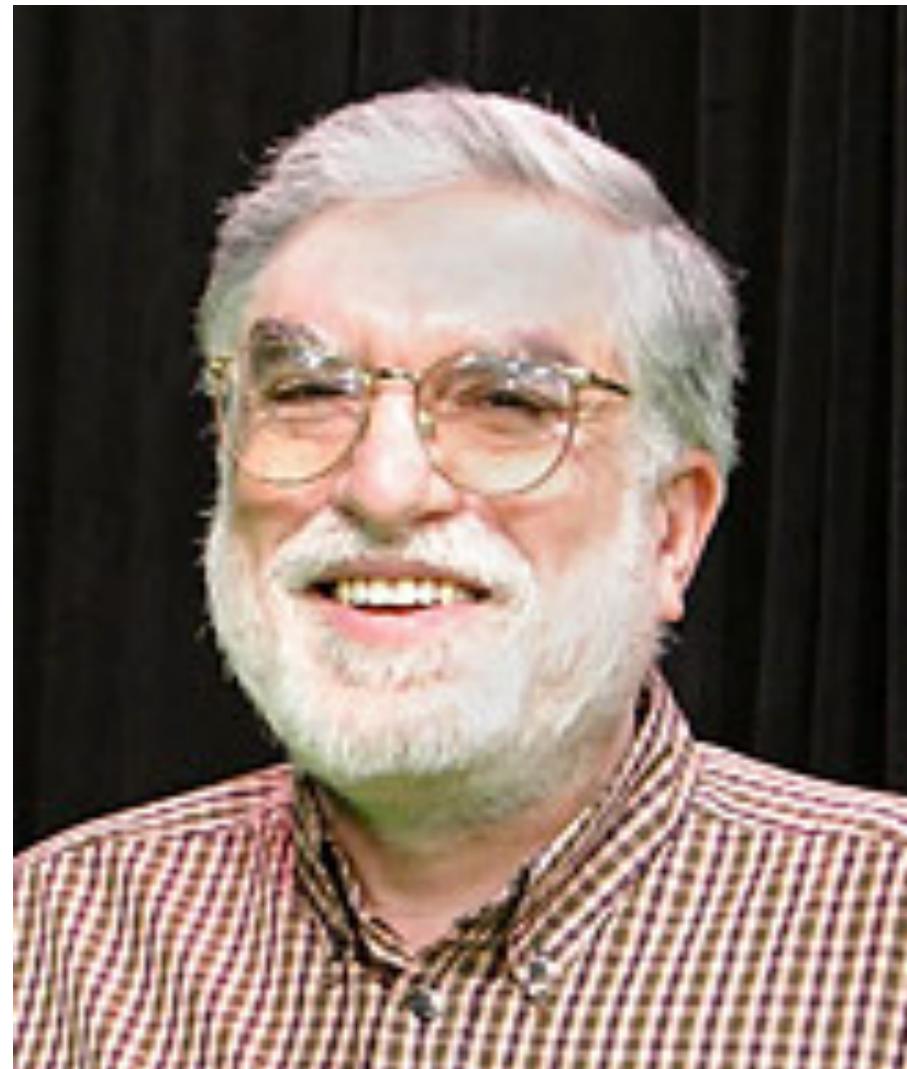
### TECTON: A LANGUAGE FOR MANIPULATING GENERIC OBJECTS

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

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**TECTON: A LANGUAGE FOR MANIPULATING  
GENERIC OBJECTS**

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# 1986-87 Libraries

## Higher Order Programming

The image shows the front cover of a technical report. The title 'Higher Order Programming' is at the top left. Below it is the subtitle 'USING TOURNAMENT TREES TO SORT'. The authors' names, 'ALEXANDER STEPANOV AND AARON KERSHENBAUM', are listed. The report is published by 'Polytechnic University' at '333 Jay Street, Brooklyn, New York 11201'. It is associated with the 'Center for Advanced Technology In Telecommunications' and is identified as 'C.A.T.T. Technical Report 86-13'. The report is dated 'March 5, 1987'. At the bottom right, there is a logo for the 'CENTER FOR ADVANCED TECHNOLOGY IN TELECOMMUNICATIONS'.

**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  
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Higher Order Programming

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Alexander A. Stepanov, Aaron Kershenbaum and David R. Musser

March 5, 1987

1987

1987

Alex works briefly at Bell Labs

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Starts a friendship with Bjarne Stroustrup



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



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Leonhard Euler

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"De-Bourbakized"



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Nicolas Bourbaki



1987

Leonhard Euler

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Knowledge is founded on the basis of precise, quantitative laws

Knowledge is founded on the basis of precise, quantitative laws  
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
    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;
```

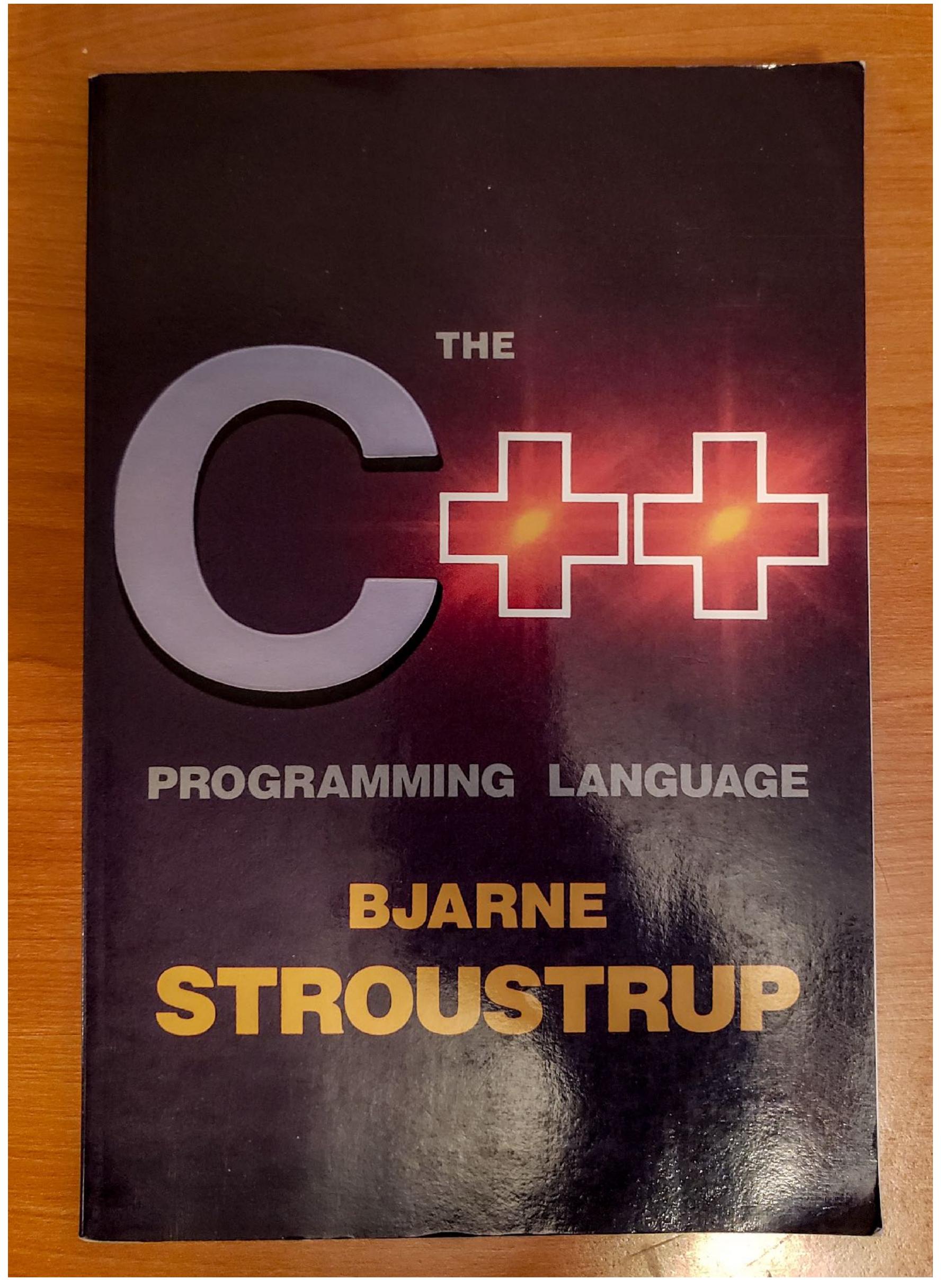
Figure 1: Body of Partition Algorithm

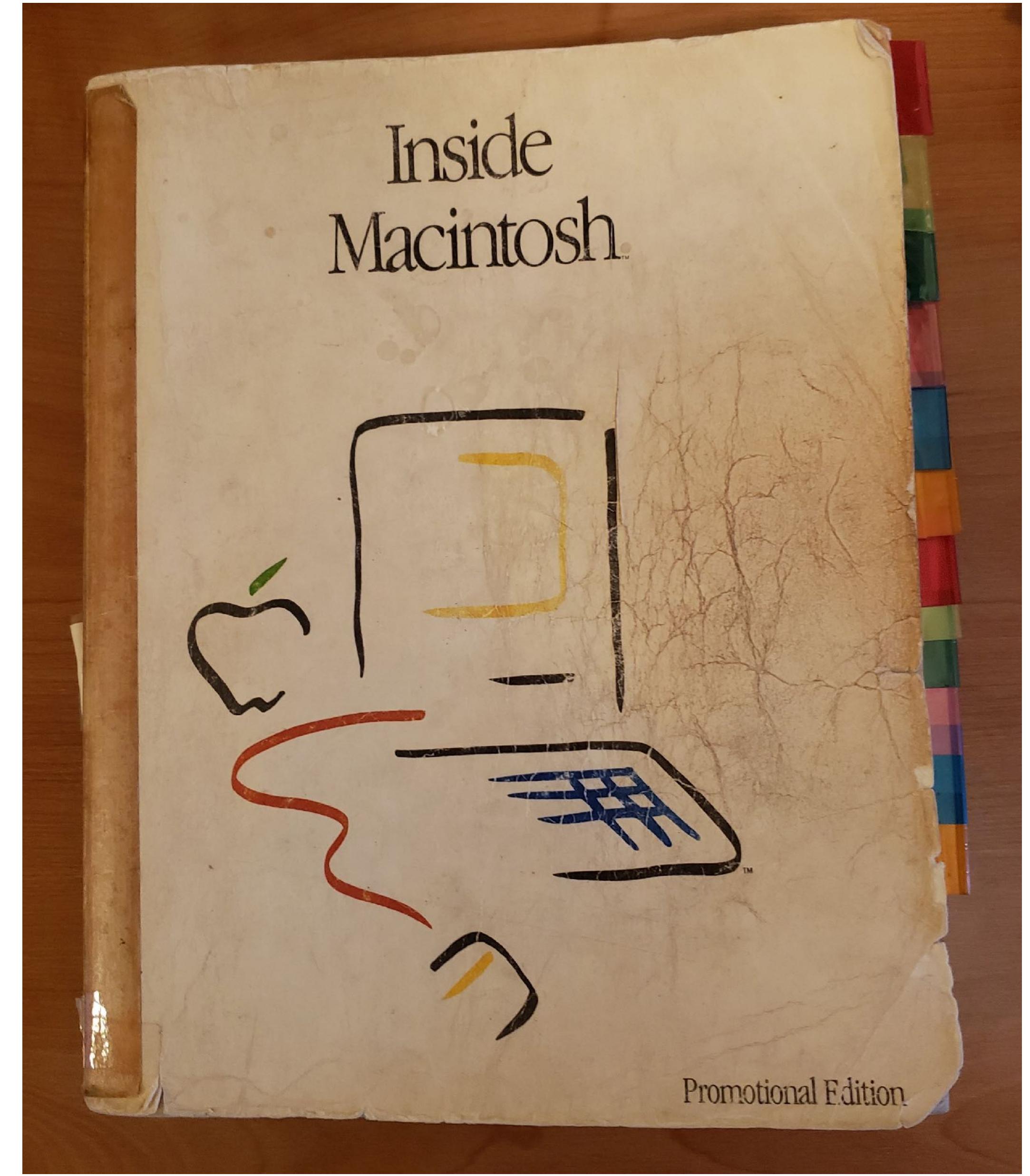
**David R. Musser  
Alexander A. Stepanov**

**The Ada®  
Generic Library**  
**Linear List Processing Packages**



Ada® is a registered trademark of the U.S. Government ADA Java Program Office





```
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.

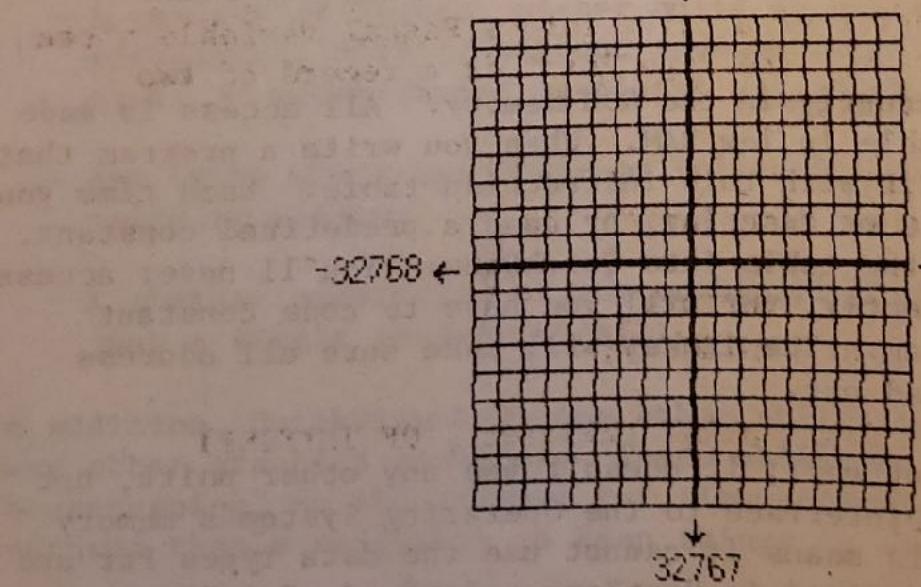


Figure 2. The Coordinate Plane

There are two distinctive features of the QuickDraw coordinate plane:

3/2/83 Espinosa-Rose

/QUICK/QUIKDRAW.2

#### THE MATHEMATICAL FOUNDATION OF QUICKDRAW 7

- 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  $(0,0)$  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
    0: (v: INTEGER;
        h: INTEGER);
    1: (vh: ARRAY [VHSelect] OF INTEGER)
END;
```

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:

3/2/83 Espinosa-Rose

/QUICK/QUIKDRAW.2

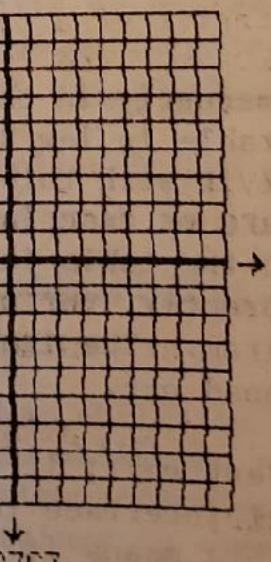
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is a representation of the QuickDraw coordinate plane:

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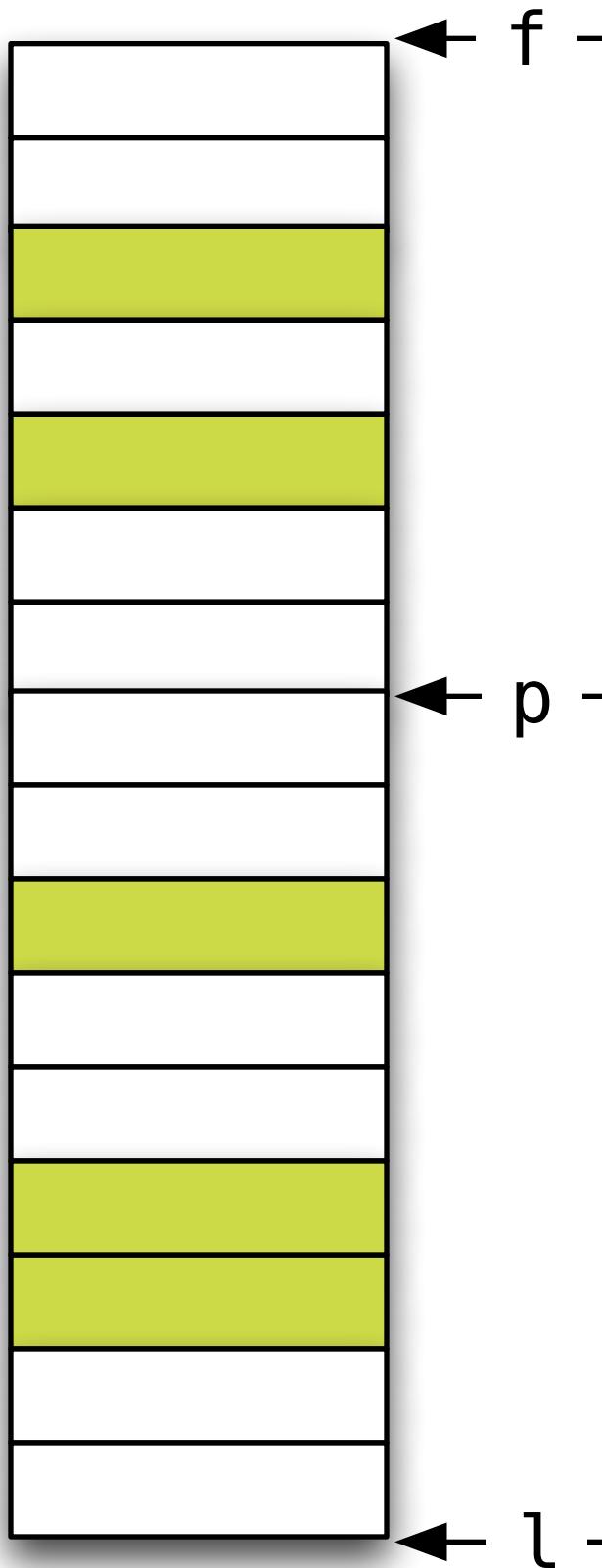
3/2/83 Espinosa-Rose

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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) };  
}
```

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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

1993

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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**

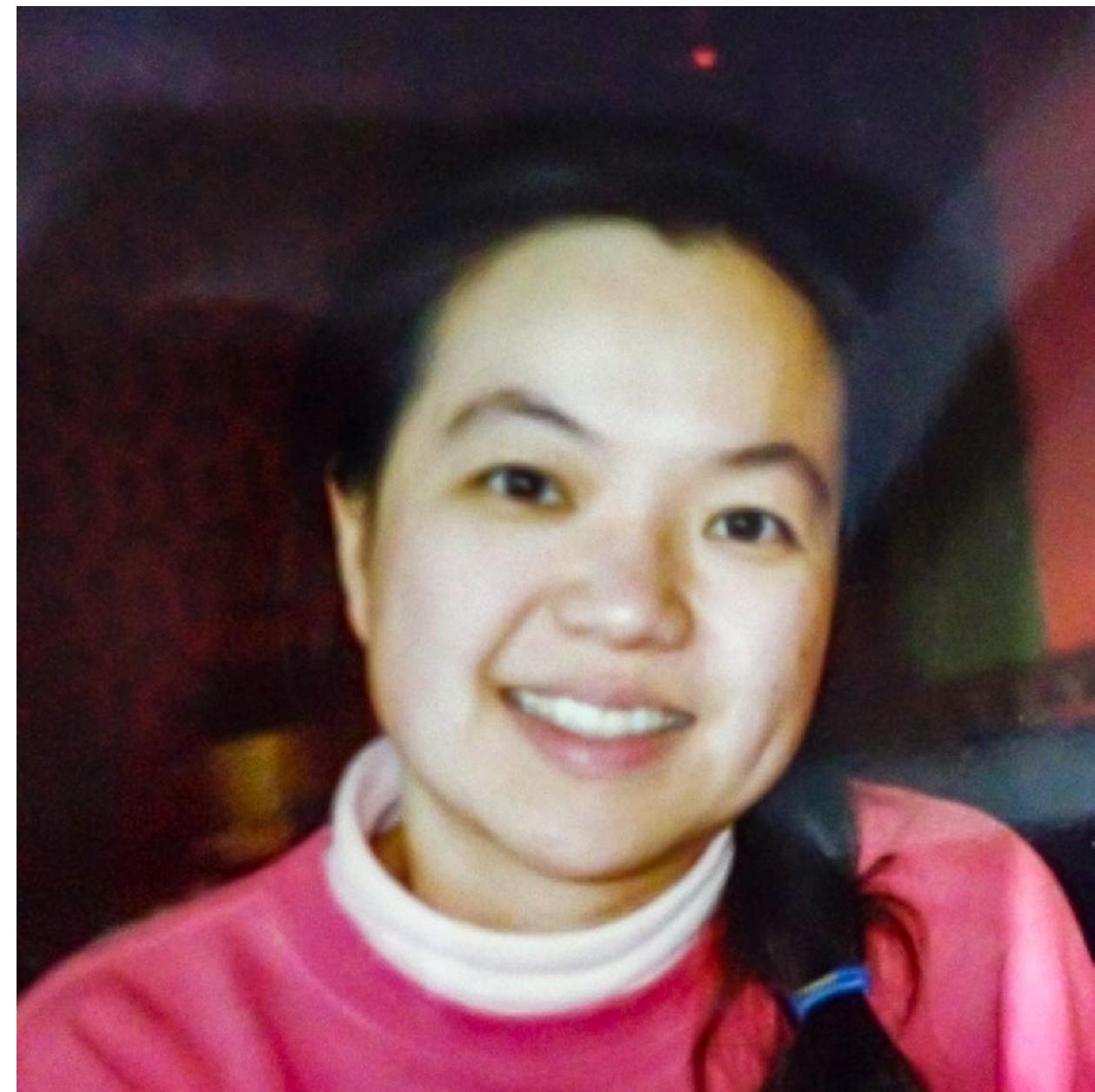
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October 31, 1995



## The Standard Template Library

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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  $X[1] \leq X[2] \leq \dots \leq X[N]$ . 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.

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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-



By Jon Bentley

# programming pearls

## 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  $X[1] \leq X[2] \leq \dots \leq X[N]$ . 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  $T = X[P]$ .

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– Jon Bentley, Programming Pearls

“I want to hire the other ten percent.”

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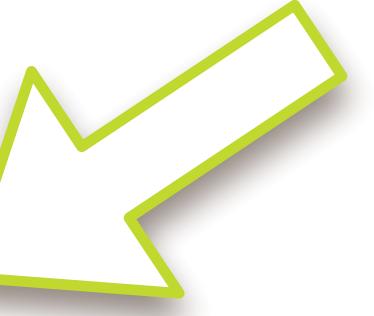
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## Jon Bentley's Solution (translated to C++)

```
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;  
    }  
}
```

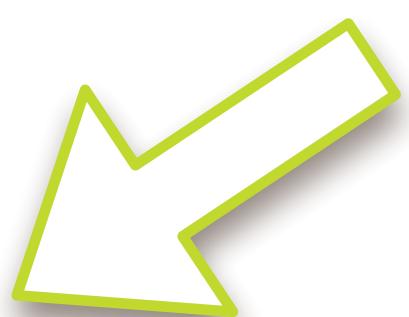
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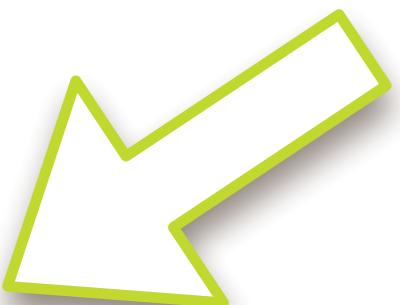
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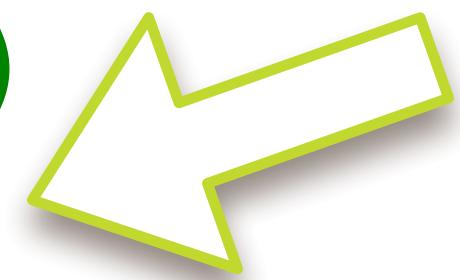


# STL implementation

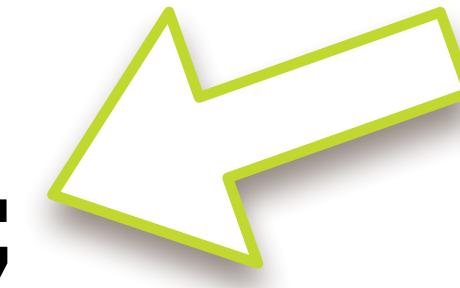
```
template <class I, // I models ForwardIterator
          class T> // T is value_type(I)
I lower_bound(I f, I l, const T& v) {
    while (f != l) {
        auto m = next(f, distance(f, l) / 2);
        if (*m < v) f = next(m);
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# Exception-Safety in Generic Components

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

David Abrahams

Dragon Systems

[David\\_Abrahams@dragonsys.com](mailto: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

James C. Dehnert and Alexander Stepanov

Silicon Graphics, Inc.  
dehnertj@acm.org, stepanov@attlabs.att.com

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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2002









## NOTES ON THE FOUNDATIONS OF PROGRAMMING

ALEX STEPANOV AND MAT MARCUS

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## NOTES ON THE FOUNDATIONS OF PROGRAMMING

ALEX STEPANOV AND MAT MARCUS

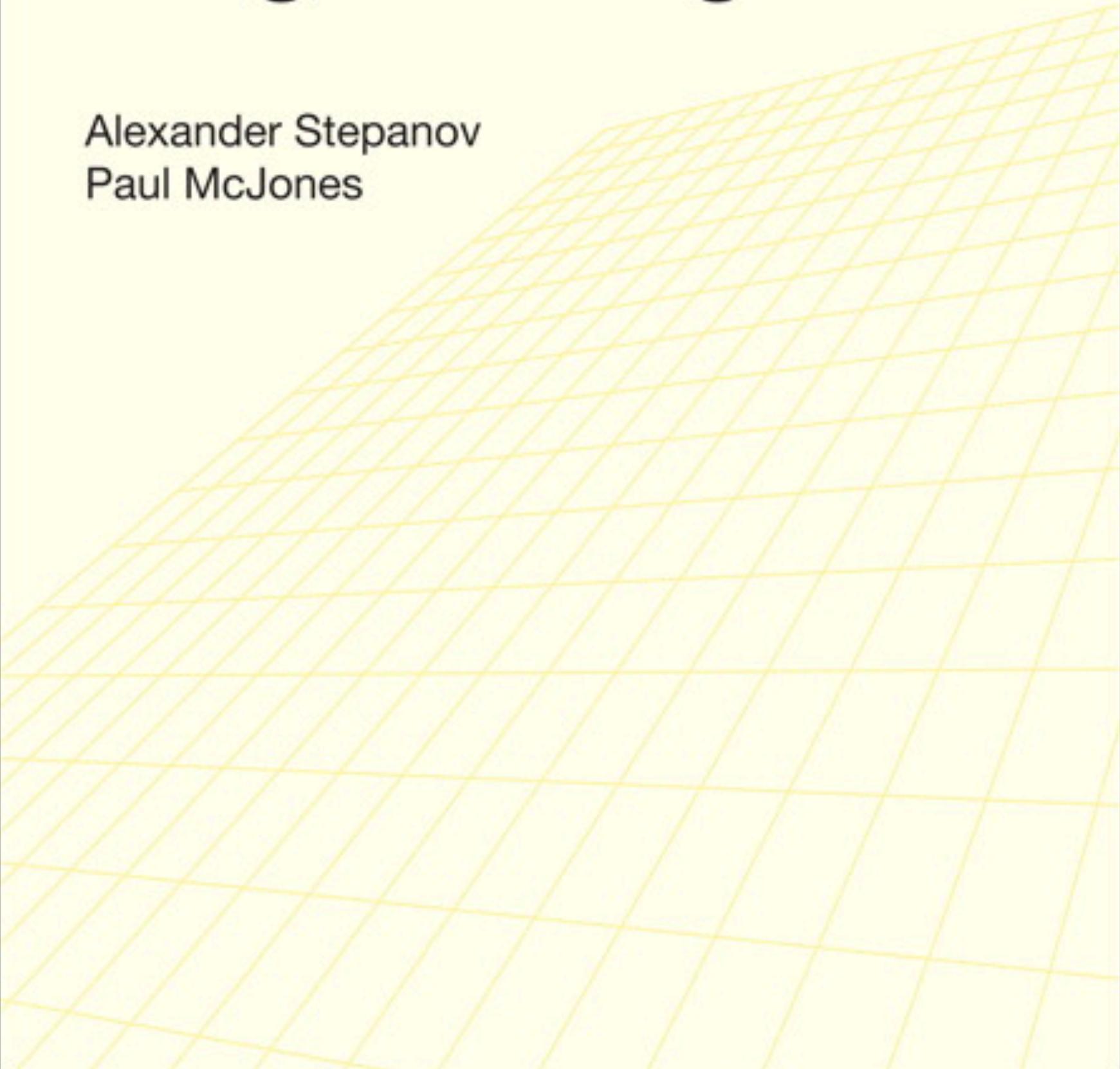
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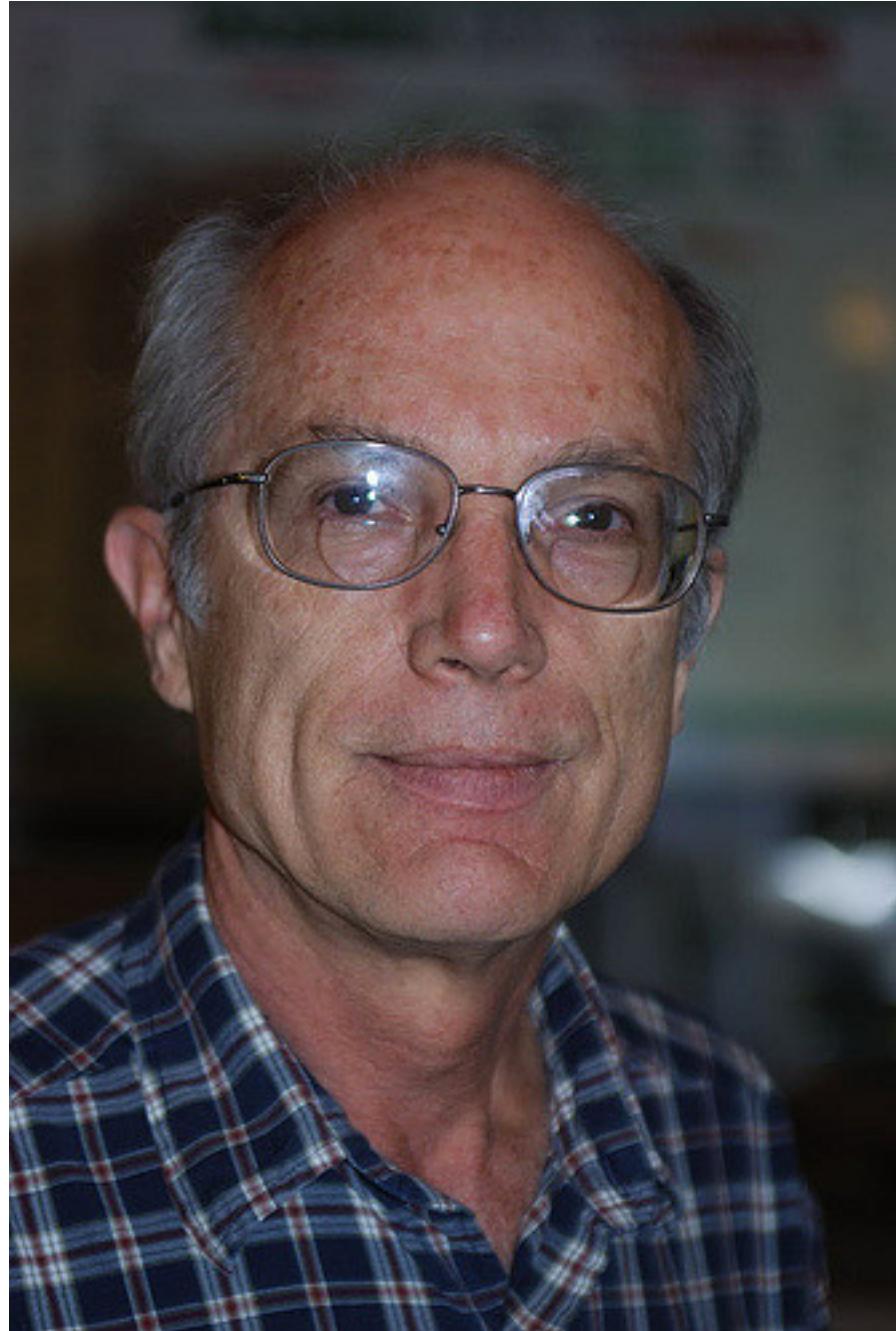
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2009

# Elements of Programming

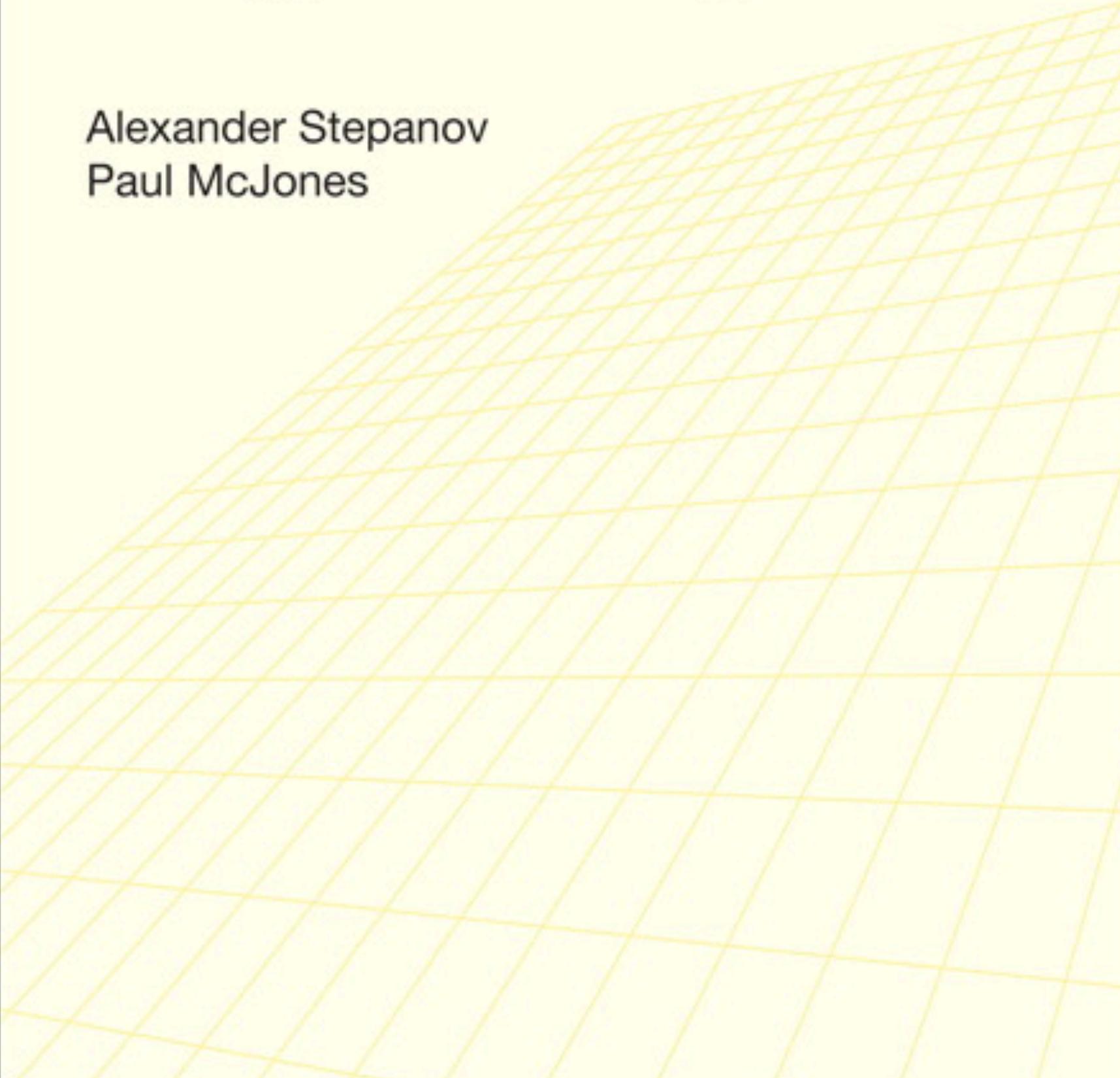
Alexander Stepanov  
Paul McJones





# Elements of Programming

Alexander Stepanov  
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  $\in |a|aa|aaa| \dots$  Optionality is expressed by square brackets, i.e.,  $[a]$  stands for  $a | \in$ . 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.<sup>[2]</sup>

<sup>[2]</sup> 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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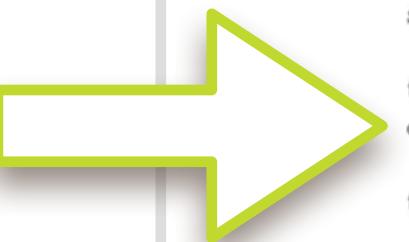
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This concept describes a homogeneous functional procedure:

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

2006

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### Abstract

Generic programming has emerged as an important technique for the development of highly reusable and efficient software libraries. In C++, generic programming is enabled by the flexibility of templates, the C++ type parametrization mechanism. However, the power of templates comes with a price: generic (template) libraries can be more difficult to use and develop than non-template libraries and their misuse results in notoriously confusing error messages. As currently defined in C++98, templates are unconstrained, and type-checking of templates is performed late in the compilation process, i.e., after the use of a template has been combined with its definition. To improve the support for generic programming in C++, we introduce *concepts* to express the syntactic and semantic behavior of types and to constrain the type parameters in a C++ template. Using concepts, type-checking of template definitions is separated from their uses, thereby making templates easier to use and easier to compile. These improvements are achieved without limiting the flexibility of templates or decreasing their performance—in fact their expressive power is increased. This paper describes the language extensions supporting concepts, their use in the expression of the C++ Standard Template Library, and their implementation in the ConceptGCC compiler. Concepts are candidates for inclusion in the upcoming revision of the ISO C++ standard, C++0x.

**Categories and Subject Descriptors** D.3.3 [*Programming Languages*]: Language Constructs and Features—Abstract data types; D.3.3 [*Programming Languages*]: Language Constructs and Features—Polymorphism; D.2.13 [*Software Engineering*]: Reusable Software—Reusable libraries

**General Terms** Design, Languages

**Keywords** Generic programming, constrained generics, parametric polymorphism, C++ templates, C++0x, concepts

### 1. Introduction

The C++ language [25, 62] supports parametrized types and functions in the form of *templates*. Templates provide a unique com-

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bination of features that have allowed them to be used for many different programming paradigms, including Generic Programming [3, 44], Generative Programming [11], and Template Metaprogramming [1, 66]. Much of the flexibility of C++ templates comes from their unconstrained nature: a template can perform any operation on its template parameters, including compile-time type computations, allowing the emulation of the basic features required for diverse programming paradigms. Another essential part of templates is their ability to provide abstraction without performance degradation: templates provide sufficient information to a compiler's optimizers (especially the inliner) to generate code that is optimal in both time and space.

Consequently, templates have become the preferred implementation style for a vast array of reusable, efficient C++ libraries [2, 6, 14, 20, 32, 54, 55, 65], many of which are built upon the Generic Programming methodology exemplified by the C++ Standard Template Library (STL) [42, 60]. Aided by the discovery of numerous *ad hoc* template techniques [28, 46, 56, 66, 67], C++ libraries are becoming more powerful, more flexible, and more expressive.

However, these improvements come at the cost of implementation complexity [61, 63]: authors of C++ libraries typically rely on a grab-bag of template tricks, many of which are complex and poorly documented. Where library interfaces are rigorously separated from library implementation, the complexity of implementation of a library is not a problem for its users. However, templates rely on the absence of modular (separate) type-checking for flexibility and performance. Therefore, the complexities of library implementation leak through to library users. This problem manifests itself most visibly in spectacularly poor error messages for simple mistakes. Consider:

```
list<int> lst;
sort(lst.begin(), lst.end());
```

Attempting to compile this code with a recent version of the GNU C++ compiler [17] produces more than two kilobytes of output, containing six different error messages. Worse, the errors reported provide line numbers and file names that point to the implementation of the STL `sort()` function and its helper functions. The only clue provided to users that this error was triggered by their own code (rather than by a bug in the STL implementation) is the following innocuous line of output:

```
sort_list.cpp:8: instantiated from here
```

The actual error, in this case, is that the STL `sort()` requires a pair of Random Access Iterators, i.e., iterators that can move any number of steps forward or backward in constant time. The STL



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:

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Jeremiah Willcock, Indiana University  
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## Abstract

This report presents a concept design for the algorithms part of the STL and outlines the design of the supporting language mechanism. Both are radical simplifications of what was proposed in the C++0x draft. In particular, this design consists of only 41 concepts (including supporting concepts), does not require concept maps, and (perhaps most importantly) does not resemble template metaprogramming.

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†Participated in editing of this report.



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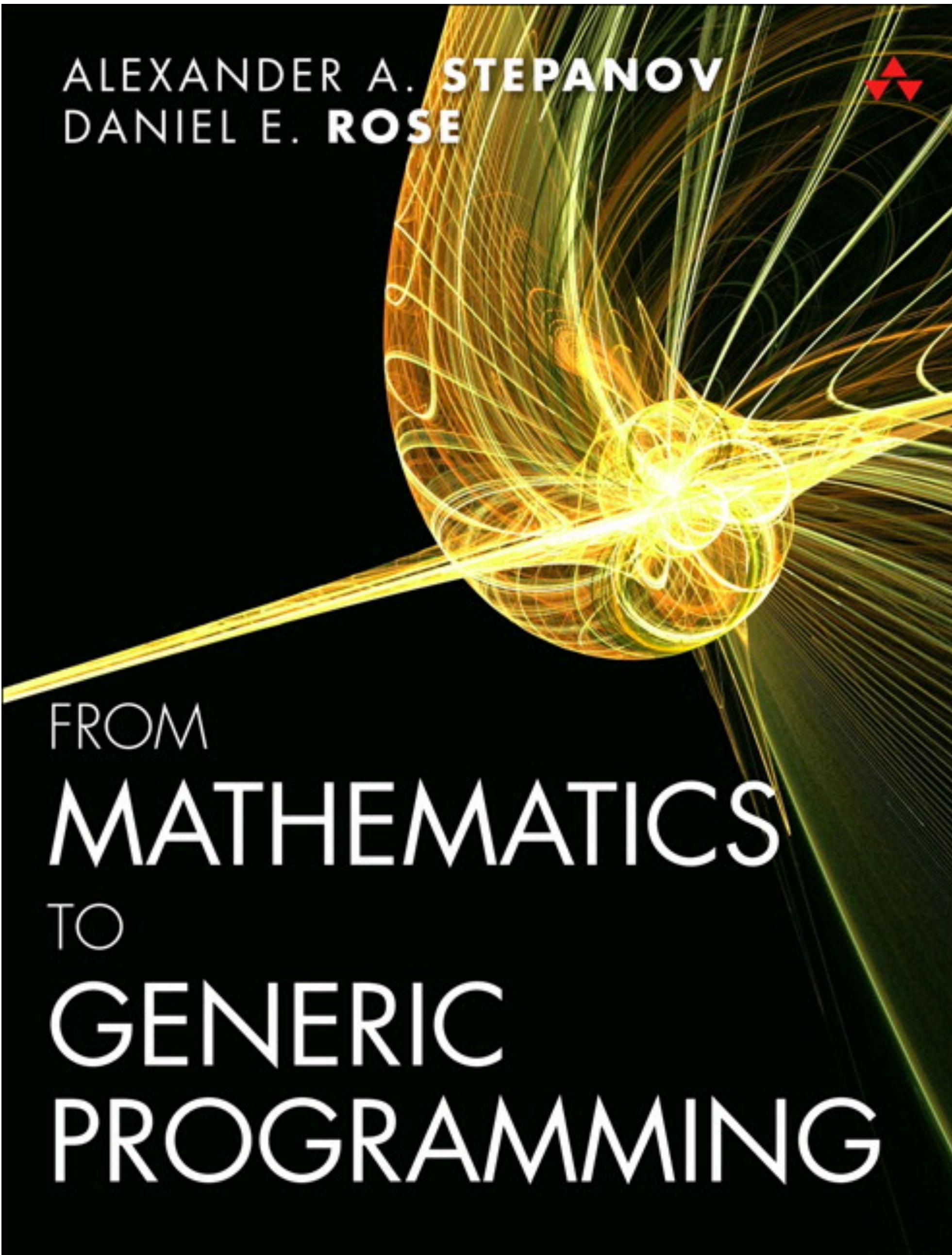
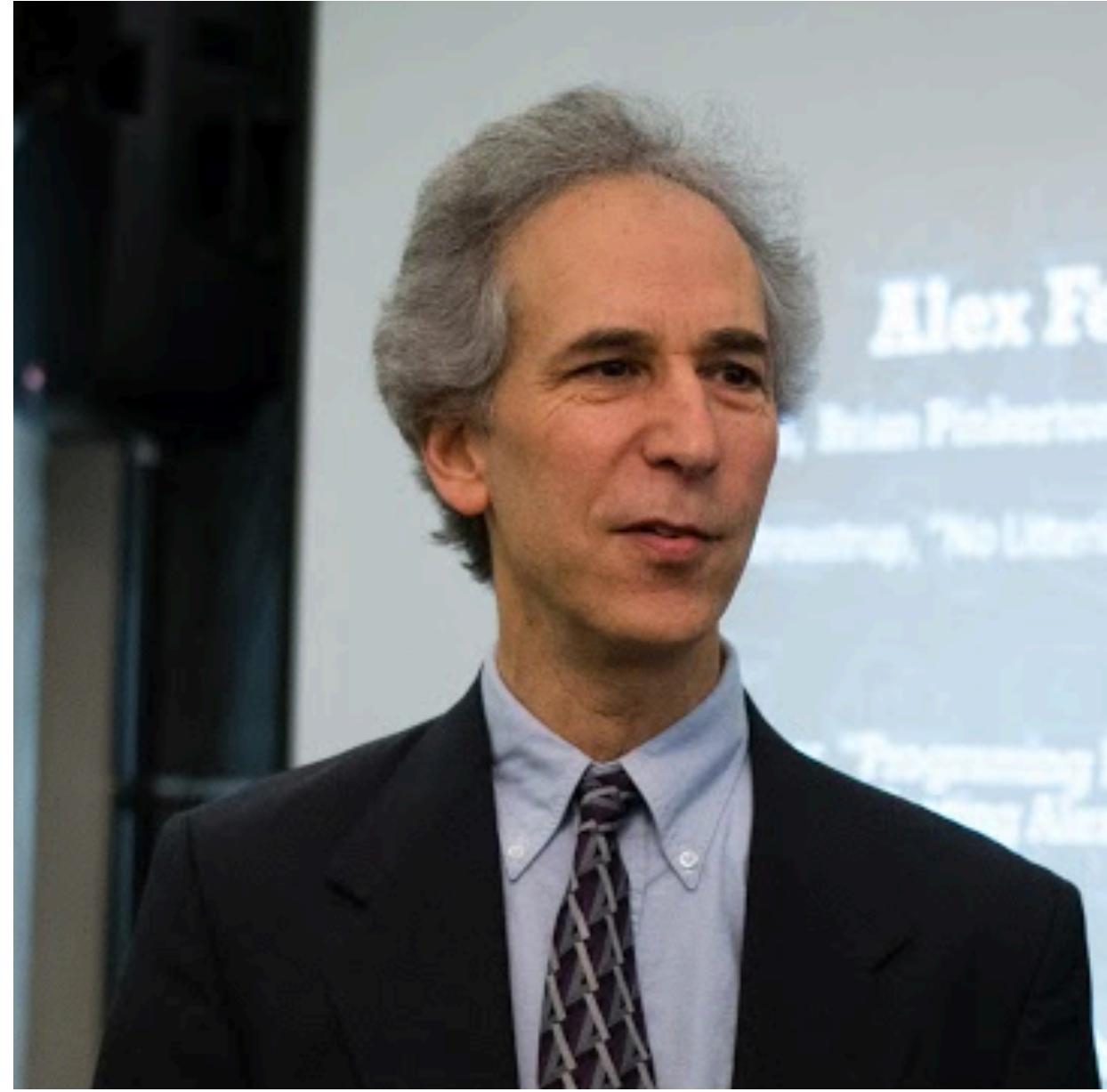
<sup>†</sup>Participated in editing of this report.

2015

ALEXANDER A. STEPANOV  
DANIEL E. ROSE



FROM  
**MATHEMATICS**  
TO  
**GENERIC**  
**PROGRAMMING**



2016



2020

## 17 Templates

[temp]

- <sup>1</sup> 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-clauseopt

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 ]

- <sup>2</sup> 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*.

- <sup>3</sup> 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 } };
}

```

*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 } };
```

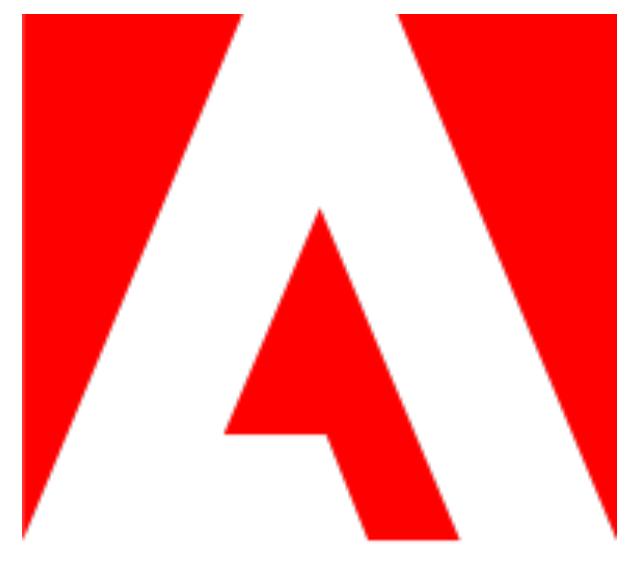


“Generic programming is about abstracting and classifying algorithms and data structures.

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



**Adobe**

# References

Much of the material in this talk can be found at

<http://stepanovpapers.com/>

A special thanks to Paul McJones for organizing this site

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