COP4020 Programming Languages

Introduction

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Based on notes by Robert van Engelen

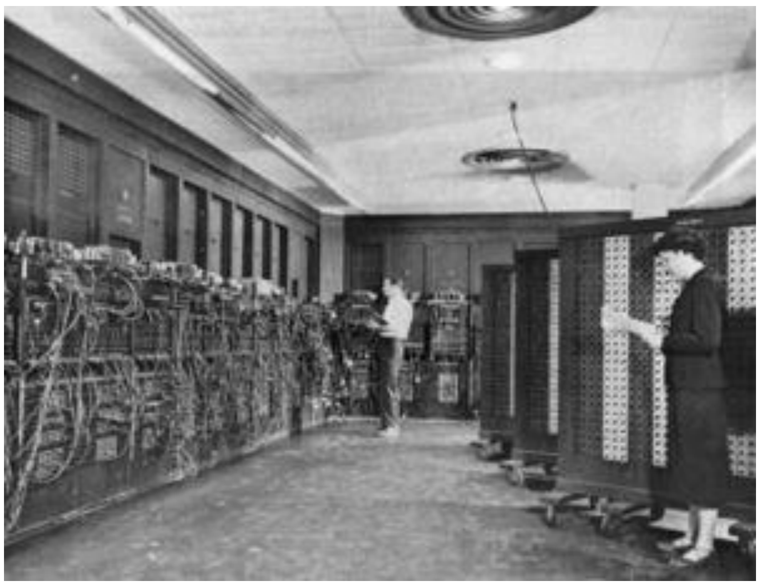
Course Objectives

- Improve the background for choosing appropriate programming languages
- Be able to program in *procedural*, *object-oriented*, *functional*, and *logical* programming languages
- Understand the significance of the design of a programming language and its implementation in a *compiler* or *interpreter*
- Enhance the ability to learn new programming languages
- Increase the capacity to express general programming concepts and to choose among alternative ways to express things in a particular programming language
- Simulate useful features in languages that lack them
- Understand how programs are parsed and translated by a compiler
- Be able, in principle, to design a new programming language

Course Outline

1. **Introduction**: History, overview, and classification of programming languages
2. **Functional Programming**: Programming with Scheme and Haskell
3. **Logic Programming**: Programming with Prolog
4. **Compilers and Interpreters**: How programs are translated into machine code
5. **Syntax**: How syntax is defined and how syntax can impact ease-of-use
6. **Semantics**: How the meaning and behavior of programming constructs can be defined and interpreted
7. **Axiomatic Semantics**: How programs can be analyzed and proven correct
8. **Names, Scopes, and Bindings**: How and when bindings for local names are defined in languages with scoping rules
9. **Control Flow**: How programming constructs define control flow and how the choice of constructs can affect programming style
10. **Subroutines and Parameter Passing**: How the subroutine calling mechanism is implemented and how and when parameters are passed and evaluated
11. **Exception Handling**: How to improve the robustness of programs

Important Events in Programming Language History



ENIAC (1946)

- 1940s: The first electronic computers were monstrous contraptions
  - Programmed in binary machine code by hand via switches and later by card readers and paper tape readers
  - Code is not reusable or relocatable
  - Computation and machine maintenance were difficult: machines had short mean-time to failure (MTTF) because vacuum tubes regularly burned out
  - The term “bug” originated from a bug that reportedly roamed around in a machine causing short circuits

Assembly Languages

- **Assembly languages** were invented to allow machine operations to be expressed in mnemonic abbreviations
  - Enables larger, reusable, and relocatable programs
  - Actual machine code is produced by an assembler
  - Early assemblers had a one-to-one correspondence between assembly and machine instructions
- **"Speedcoding"**: expansion of macros into multiple machine instructions to achieve a form of higher-level programming

Assembly Language Example

```
      addiu   sp,sp,-32
      sw      ra,20(sp)
      jal     getint
      nop
      jal     getint
      sw      v0,28(sp)
      lw      a0,28(sp)
      move    v1,v0
      beq     a0,v0,D
      slt     at,v1,a0
A:    beq     at,zero,B
      nop
      b       C
      subu    a0,a0,v1
B:    subu    v1,v1,a0
C:    bne     a0,v1,A
      slt     at,v1,a0
D:    jal     putint
      nop
      lw      ra,20(sp)
      addiu   sp,sp,32
      jr      ra
      move    v0,zero
```

- Example MIPS assembly program to compute GCD
- Example MIPS R4000 machine code of the assembly program

```
27bdffd0 afbf0014 0c1002a8 00000000
   0c1002a8 afa2001c 8fa4001c
00401825 10820008 0064082a 10200003
   00000000 10000002 00832023
00641823 1483fffa 0064082a 0c1002b2
   00000000 8fbf0014 27bd0020
03e00008 00001025
```

Actual MIPS R4400 IC

The First High-Level Programming Language

- Mid 1950s: development of **FORTRAN** (FORmula TRANslator), the arguably first higher-level language
  - Finally, programs could be developed that were machine independent!
- Main computing activity in the 50s: solve numerical problems in science and engineering
- Other high-level languages soon followed:
  - **Algol 58** was an improvement compared to Fortran
  - **COBOL** for business computing
  - **Lisp** for symbolic computing and artifical intelligence
  - **BASIC** for "beginners"
  - **C** for systems programming

FORTRAN 77 Example

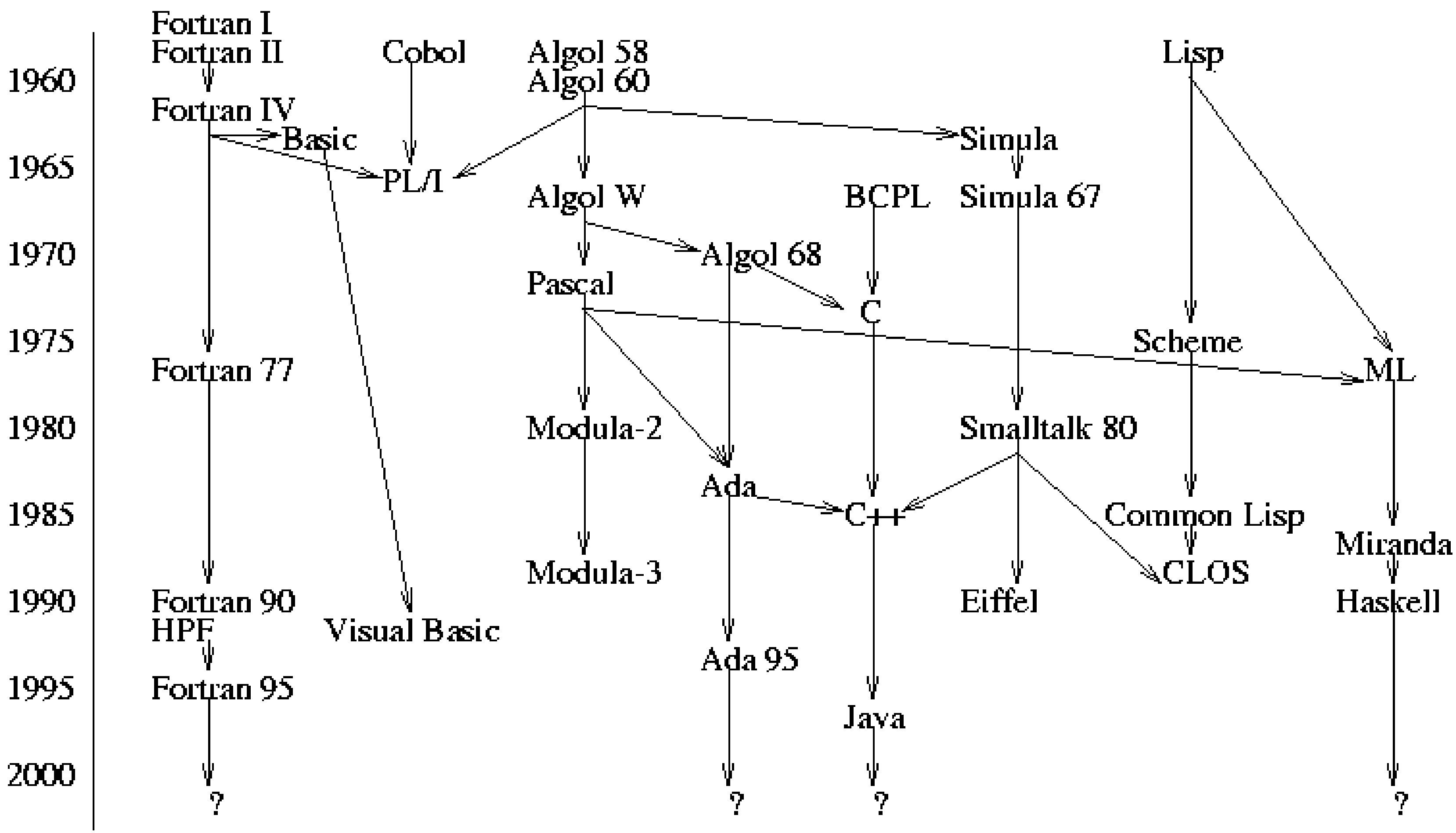
```
      PROGRAM GCD
C     variable names that start with
C           I,J,K,L,N,M are integers
C     read the parameters
      READ (*, *) I, J
C     loop while I!=J
10    IF I .NE. J THEN
      IF I .GT. J THEN
      I = I - J
      ELSE
      J = J - I
      ENDIF
      GOTO 10
      ENDIF
C     write result
      WRITE (*, *) 'GCD =', I
      END
```

- FORTRAN is still widely used for scientific, engineering, and numerical problems, mainly because very good compilers exist
- In the early days skeptics wrongly predicted that compilers could not beat hand-written machine code
- FORTRAN 77 has
  - Subroutines, if-then-else, do-loops
  - Types (primitive and arrays)
  - Variable names are upper case and limited to 6 chars
  - No recursion
  - No structs/classes, unions
  - No dynamic allocation
  - No case-statements and no while-loops

Important Events in Programming Language History

- 1980s: Object-oriented programming
  - Important innovation for software development
    - Encapsulation and inheritance
    - Dynamic binding
  - The concept of a “class” is based on the notion of an “abstract data type” (ADT) in Simula 67, a language for discrete event simulation that has class-like types but no inheritance

Genealogy of Programming Languages



Overview: FORTRAN I,II,IV,77

```
      PROGRAM AVEX
      INTEGER INTLST(99)
      ISUM = 0
C     read the length of the list
      READ (*, *) LSTLEN
      IF ((LSTLEN .GT. 0) .AND. (LSTLEN .LT. 100)) THEN
C     read the input in an array
      DO 100 ICTR = 1, LSTLEN
      READ (*, *) INTLST(ICTR)
      ISUM = ISUM + INTLST(ICTR)
100   CONTINUE
C     compute the average
      IAVE = ISUM / LSTLEN
C     write the input values > average
      DO 110 ICTR = 1, LSTLEN
      IF (INTLST(ICTR) .GT. IAVE) THEN
      WRITE (*, *) INTLST(ICTR)
      END IF
110   CONTINUE
      ELSE
      WRITE (*, *) 'ERROR IN LIST LENGTH'
      END IF
      END
```

- FORTRAN had a dramatic impact on computing in early days
- Still used for numerical computation

FORTRAN 90,95,HPF

```
      PROGRAM AVEX
      INTEGER INT_LIST(1:99)
      INTEGER LIST_LEN, COUNTER, AVERAGE
C     read the length of the list
      READ (*, *) LISTLEN
      IF ((LIST_LEN > 0) .AND. (LIST_LEN < 100)) THEN
C     read the input in an array
      DO COUNTER = 1, LIST_LEN
      READ (*, *) INT_LIST(COUNTER)
      END DO
C     compute the average
      AVERAGE = SUM(INT_LIST(1:LIST_LEN)) / LIST_LEN
C     write the input values > average
      DO COUNTER = 1, LIST_LEN
      IF (INT_LIST(COUNTER) > AVERAGE) THEN
      WRITE (*, *) INT_LIST(COUNTER)
      END IF
      END DO
      ELSE
      WRITE (*, *) 'ERROR IN LIST LENGTH'
      END IF
      END
```

- Major revisions
  - Recursion
  - Pointers
  - Records
- New control constructs
  - while-loop
- Extensive set of array operations
- HPF (High-Performance Fortran) includes constructs for parallel computation

Lisp

```
(DEFINE (avex lis)
  (filtergreater lis (/ (sum lis) (length lis)))
)
(DEFINE (sum lis)
  (COND
    ((NULL? lis) 0)
    (ELSE        (+ (CAR lis) (sum (CDR lis))))
  )
)
(DEFINE (filtergreater lis num)
  (COND
    ((NULL? lis)       '())
    ((> (CAR lis) num) (CONS (CAR lis)
                             (filtergreater (CDR lis) num)))
    (ELSE              (filtergreater (CDR lis) num)
  )
)
```

- Lisp (LIst Processing)
- The original functional language developed by McCarthy as a realization of Church's lambda calculus
- Many dialects exist, including Common Lisp and Scheme
- Very powerful for symbolic computation with lists
- Implicit memory management with garbage collection
- Influenced functional programming languages (ML, Miranda, Haskell)

Algol 60

```
comment avex program
begin
  integer array intlist [1:99];
  integer listlen, counter, sum, average;
  sum := 0;
  comment read the length of the input list
  readint (listlen);
  if (listlen > 0) L (listlen < 100) then
    begin
      comment read the input into an array
      for counter := 1 step 1 until listlen do
        begin
          readint (intlist[counter]);
          sum := sum + intlist[counter]
        end;
      comment compute the average
      average := sum / listlen;
      comment write the input values > average
      for counter := 1 step 1 until listlen do
        if intlist[counter] > average then
          printint (intlist[counter])
    end
  else
    printstring ("Error in input list length")
end
```

- The original block-structured language
  - Local variables in a statement block
- First use of Backus-Naur Form (BNF) to formally define language grammar
- All subsequent imperative programming languages are based on it
- No I/O and no character set
- Not widely used in the US
- Unsuccessful successor Algol 68 is large and relatively complex

COBOL

```
IDENTIFICATION DIVISION.
PROGRAM-ID.  EXAMPLE.

ENVIRONMENT DIVISION.
CONFIGURATION SECTION.
SOURCE-COMPUTER.   IBM-370.
OBJECT-COMPUTER.   IBM-370.

DATA DIVISION.
WORKING-STORAGE SECTION.
77 FAHR  PICTURE 999.
77 CENT  PICTURE 999.

PROCEDURE DIVISION.
DISPLAY 'Enter Fahrenheit ' UPON CONSOLE.
ACCEPT FAHR FROM CONSOLE.
COMPUTE CENT = (FAHR- 32) * 5 / 9.
DISPLAY 'Celsius is ' CENT UPON CONSOLE.
GOBACK.
```

- Originally developed by the Department of Defense
- Intended for business data processing
- Extensive numerical formatting features and decimal number storage
- Introduced the concept of records and nested selection statement
- Programs organized in divisions:
  IDENTIFICATION: Program identification
  ENVIRONMENT: Types of computers used
  DATA: Buffers, constants, work areas
  PROCEDURE: The processing parts (program logic).

BASIC

```
REM avex program
  DIM intlist(99)
  sum = 0
REM read the length of the input list
  INPUT listlen
  IF listlen > 0 AND listlen < 100 THEN
REM read the input into an array
    FOR counter = 1 TO listlen
      INPUT intlist(counter)
      sum = sum + intlist(counter)
    NEXT counter
REM compute the average
    average = sum / listlen
REM write the input values > average
    FOR counter = 1 TO listlen
      IF intlist(counter) > average THEN
        PRINT intlist(counter);
    NEXT counter
  ELSE
    PRINT "Error in input list length"
  END IF
END
```

- BASIC (Beginner's All-Purpose Symbolic Instruction Code)
- Intended for interactive use (intepreted) and easy for "beginners"
- Goals: easy to learn and use for non-science students
- Structure of early basic dialects were similar to Fortran
- Classic Basic
- QuickBasic (see example)
- MS Visual Basic is a popular dialect

PL/I

```
AVEX: PROCEDURE OPTIONS (MAIN);
  DECLARE INTLIST (1:99) FIXED;
  DECLARE (LISTLEN, COUNTER, SUM, AVERAGE) FIXED;
  SUM = 0;
  /* read the input list length */
  GET LIST (LISTLEN);
  IF (LISTLEN > 0) & (LISTLEN < 100) THEN
    DO;
    /* read the input into an array */
    DO COUNTER = 1 TO LISTLEN;
      GET LIST (INTLIST(COUNTER));
      SUM = SUM + INTLIST(COUNTER);
    END;
    /* compute the average */
    AVERAGE = SUM / LISTLEN;
    /* write the input values > average */
    DO COUNTER = 1 TO LISTLEN;
      IF INTLIST(COUNTER) > AVERAGE THEN
        PUT LIST (INTLIST(COUNTER));
    END;
  ELSE
    PUT SKIP LIST ('ERROR IN INPUT LIST LENGTH');
END AVEX;
```

- Developed by IBM
  - Intended to replace FORTRAN, COBOL, and Algol
- Introduced exception handling
- First language with pointer data type
- Poorly designed, too large, too complex

Ada and Ada95

```
with TEXT_IO;
use TEXT_IO;
procedure AVEX is
  package INT_IO is new INTEGER_IO (INTEGER);
  use INT_IO;
  type INT_LIST_TYPE is array (1..99) of INTEGER;
  INT_LIST : INT_LIST_TYPE;
  LIST_LEN, SUM, AVERAGE : INTEGER;
  begin
    SUM := 0;
    -- read the length of the input list
    GET (LIST_LEN);
    if (LIST_LEN > 0) and (LIST_LEN < 100) then
      -- read the input into an array
      for COUNTER := 1 .. LIST_LEN loop
        GET (INT_LIST(COUNTER));
        SUM := SUM + INT_LIST(COUNTER);
      end loop;
      -- compute the average
      AVERAGE := SUM / LIST_LEN;
      -- write the input values > average
      for counter := 1 .. LIST_LEN loop
        if (INT_LIST(COUNTER) > AVERAGE) then
          PUT (INT_LIST(COUNTER));
          NEW_LINE;
        end if
      end loop;
    else
      PUT_LINE ("Error in input list length");
    end if;
  end AVEX;
```

- Originally intended to be the standard language for all software commissioned by the US Department of Defense
- Very large
- Elaborate support for packages, exception handling, generic program units, concurrency
- Ada 95 is a revision developed under government contract by a team at Intermetrics, Inc.
  - Adds objects, shared-memory synchronization, and several other features

Smalltalk-80

```
class name                  Avex
superclass                  Object
instance variable names     intlist
"Class methods"
"Create an instance"
  new
    ^ super new
"Instance methods"
"Initialize"
  initialize
    intlist <- Array new: 0
"Add int to list"
  add: n | oldintlist |
    oldintlist <- intlist.
    intlist <- Array new: intlist size + 1.
    intlist <- replaceFrom: 1 to: intlist size with: oldintlist.
    ^ intlist at: intlist size put: n
"Calculate average"
  average | sum |
    sum <- 0.
    1 to: intlist size do:
      [:index | sum <- sum + intlist at: index].
    ^ sum // intlist size
"Filter greater than average"
  filtergreater: n | oldintlist i |
    oldintlist <- intlist.
    i <- 1.
    1 to: oldintlist size do:
      [:index | (oldintlist at: index) > n
          ifTrue: [oldintlist at: i put: (oldintlist at: index)]]
    intlist <- Array new: oldintlist size.
    intlist replaceFrom: 1 to: oldintlist size with: oldintlist
```

- Developed by XEROX PARC: first IDE with windows-based graphical user interfaces (GUIs)
- The first full implementation of an object-oriented language
- Example run:

```
av <- Avex new
av initialize
av add: 1
1
av add: 2
2
av add: 3
3
av filtergreater: av average
av at: 1
3
```

Prolog

```
avex(IntList, GreaterThanAveList) :-
    sum(IntList, Sum),
    length(IntList, ListLen),
    Average is Sum / ListLen,
    filtergreater(IntList, Average, GreaterThanAveList).
% sum(+IntList, -Sum)
% recursively sums integers of IntList
sum([Int | IntList], Sum) :-
    sum(IntList, ListSum),
    Sum is Int + ListSum.
sum([], 0).
% filtergreater(+IntList, +Int, -GreaterThanIntList)
% recursively remove all integers <= Int from IntList
filtergreater([AnInt | IntList], Int, [AnInt |
    GreaterThanIntList]) :-
    AnInt > Int, !,
    filtergreater(IntList, Int, GreaterThanIntList).
filtergreater([AnInt | IntList], Int, GreaterThanIntList) :-
    filtergreater(IntList, Int, GreaterThanIntList).
filtergreater([], Int, []).
```

- The most widely used logic programming language
- Declarative: states what you want, not how to get it
- Based on formal logic

Pascal

```
program avex(input, output);
  type
    intlisttype = array [1..99] of integer;
  var
    intlist : intlisttype;
    listlen, counter, sum, average : integer;
begin
  sum := 0;
  (* read the length of the input list *)
  readln(listlen);
  if ((listlen > 0) and (listlen < 100)) then
    begin
      (* read the input into an array *)
      for counter := 1 to listlen do
        begin
          readln(intlist[counter]);
          sum := sum + intlist[counter]
        end;
      (* compute the average *)
      average := sum / listlen;
      (* write the input values > average *)
      for counter := 1 to listlen do
        if (intlist[counter] > average) then
          writeln(intlist[counter])
    end
  else
    writeln('Error in input list length')
end.
```

- Designed by Swiss professor Niklaus Wirth
- Designed for teaching "structured programming"
- Small and simple
- Had a strong influence on subsequent high-level languages Ada, ML, Modula

Haskell

- The leading purely functional language, based on Miranda
- Includes curried functions, higher-order functions, non-strict semantics, static polymorphic typing, pattern matching, list comprehensions, modules, monadic I/O, and layout (indentation)-based syntactic grouping

```
sum []    = 0
sum (a:x) = a + sum x

avex []    = []
avex (a:x) = [n | n <- a:x, n > sum (a:x) / length (a:x)]
```

C (ANSI C, K&R C)

```
main()
{   int intlist[99], listlen, counter, sum, average;
    sum = 0;
    /* read the length of the list */
    scanf("%d", &listlen);
    if (listlen > 0 && listlen < 100)
    {   /* read the input into an array */
        for (counter = 0; counter < listlen; counter++)
        {   scanf("%d", &intlist[counter]);
            sum += intlist[counter];
        }
        /* compute the average */
        average = sum / listlen;
        /* write the input values > average */
        for (counter = 0; counter < listlen; counter++)
            if (intlist[counter] > average)
                printf("%d\n", intlist[counter]);
    }
    else
        printf("Error in input list length\n");
}
```

- One of the most successful programming languages
- Primarily designed for systems programming but more broadly used
- Powerful set of operators, but weak type checking and no dynamic semantic checks

C++

```
main()
{   std::vector<int> intlist;
    int listlen;
    /* read the length of the list */
    std::cin >> listlen;
    if (listlen > 0 && listlen < 100)
    {   int sum = 0;
        /* read the input into an STL vector */
        for (int counter = 0; counter < listlen; counter++)
        {   int value;
            std::cin >> value;
            intlist.push_back(value);
            sum += value;
        }
        /* compute the average */
        int average = sum / listlen;
        /* write the input values > average */
        for (std::vector<int>::const_iterator it = intlist.begin();
                                          it != intlist.end(); ++it)
            if ((*it) > average)
                std::cout << (*it) << std::endl;
    }
    else
        std::cerr << "Error in input list length" << std::endl;
}
```

- The most successful of several object-oriented successors of C
- Evolved from C and Simula 67
- Large and complex, partly because it supports both procedural and object-oriented programming

Java

```
import java.io;
class Avex
{   public static void main(String args[]) throws IOException
    {   DataInputStream in = new DataInputStream(System.in);
        int listlen, counter, sum = 0, average;
        int [] intlist = int[100];
        // read the length of the list
        listlen = Integer.parseInt(in.readLine());
        if (listlen > 0 && listlen < 100)
        {   // read the input into an array
            for (counter = 0; counter < listlen; counter++)
            {   intlist[counter] =
    Integer.valueOf(in.readline()).intValue();
                sum += intlist[counter];
            }
            // compute the average
            average = sum / listlen;
            // write the input values > average
            for (counter = 0; counter < listlen; counter++)
            {   if (intlist[counter] > average)
                    System.out.println(intlist[counter] + "\n");
            }
        }
        else
          System.out.println("Error in input length\n");
    }
}
```

- Developed by Sun Microsystems
- Based on C++, but significantly simplified
- Supports only object-oriented programming
- Safe language (e.g. no pointers but references, strongly typed, and implicit garbage collection)
- Portable and machine-independent with Java virtual machine (JVM)

Other Notable Languages

- C#
  - Similar to Java, but platform dependent (MS .NET)
  - Common Language Runtime (CLR) manages objects that can be shared among the different languages in .NET
- Simula 67
  - Based on Algol 60
  - Primarily designed for discrete-event simulation
  - Introduced concept of coroutines and the class concept for data abstraction
- APL
  - Intended for interactive use ("throw-away" programming)
  - Highly expressive functional language makes programs short, but hard to read
- Scripting languages
  - Perl, Python, Ruby, …

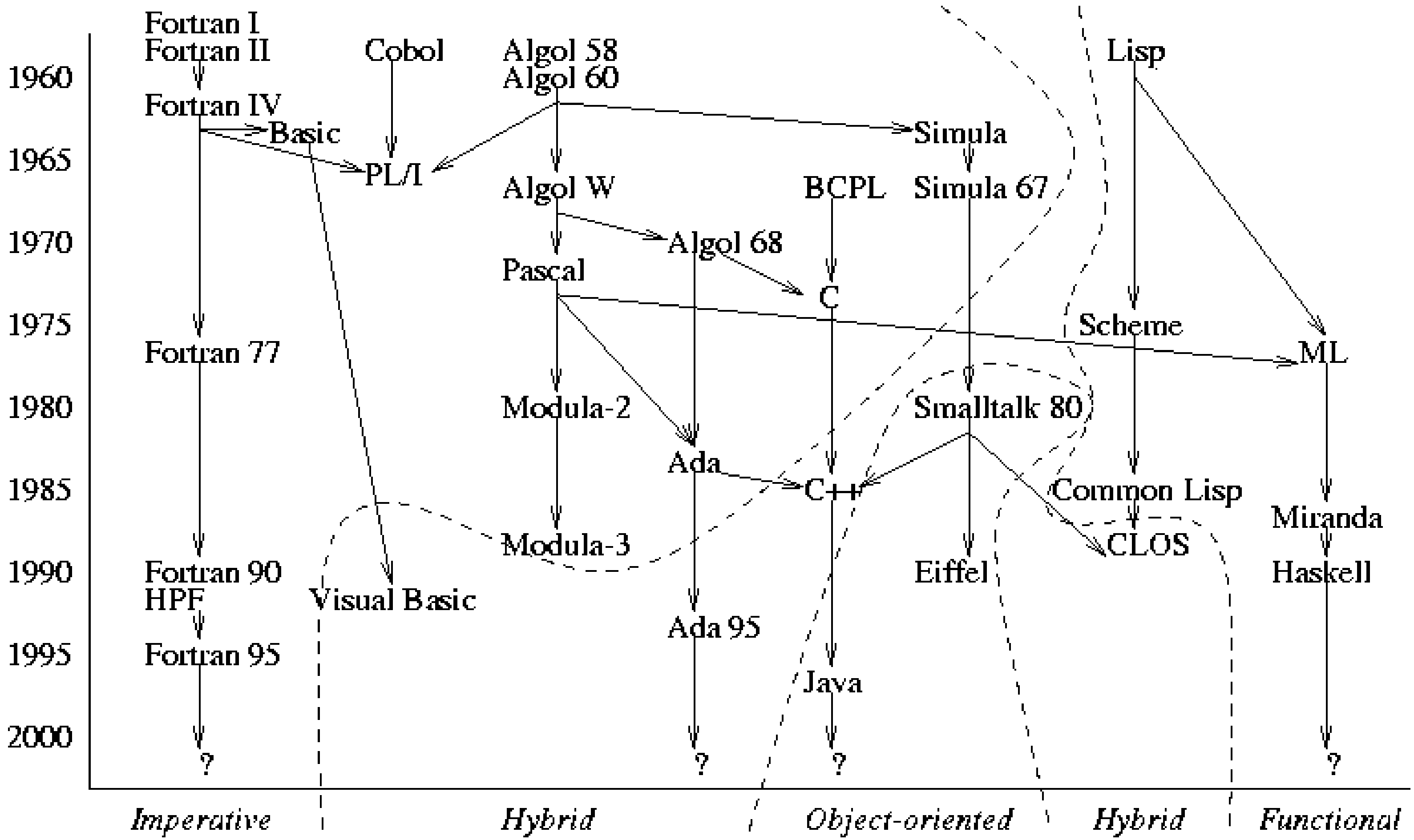
Why are There so Many Programming Languages?

- Evolution
  - Design considerations: What is a good or bad programming construct?
  - Early 70s: structured programming in which goto-based control flow was replaced by high-level constructs (e.g. while loops and case statements)
  - Late 80s: nested block structure gave way to object-oriented structures
- Special Purposes
  - Many languages were designed for a specific problem domain, e.g:
    - Scientific applications
    - Business applications
    - Artificial intelligence
    - Systems programming
    - Internet programming
- Personal Preference
  - The strength and variety of personal preference makes it unlikely that anyone will ever develop a universally accepted programming language

What Makes a Programming Language Successful?

- Expressive Power
  - Theoretically, all languages are equally powerful (Turing complete)
  - Language features have a huge impact on the programmer's ability to read, write, maintain, and analyze programs
  - Abstraction facilities enhance expressive power
- Ease of Use for Novice
  - Low learning curve and often interpreted, e.g. Basic and Logo
- Ease of Implementation
  - Runs on virtually everything, e.g. Basic, Pascal, and Java
- Open Source
  - Freely available, e.g. Java
- Excellent Compilers and Tools
  - Fortran has extremely good compilers
  - Supporting tools to help the programmer manage very large projects
- Economics, Patronage, and Inertia
  - Powerful sponsor: Cobol, PL/I, Ada
  - Some languages remain widely used long after "better" alternatives

Classification of Programming Languages



Classification of Programming Languages

Declarative Implicit solution "What the computer should do”	**Functional** (Lisp, Scheme, ML, Haskell) **Logical** (Prolog) **Dataflow**
Imperative Explicit solution "How the computer should do it”	**Procedural** "von Neumann" (Fortran, C) **Object-oriented** (Smalltalk, C++, Java)

Contrasting Examples

Procedural (C):

```
int gcd(int a, int b)
{ while (a != b)
    if (a > b) a = a-b; else b = b-a;
  return a;
}
```

Functional (Haskell):

```
gcd a b
  | a == b = a
  | a >  b = gcd (a-b) b
  | a <  b = gcd a (b-a)
```

Logical (Prolog):

```
gcd(A, A, A).
gcd(A, B, G) :- A > B, N is A-B, gcd(N, B, G).
gcd(A, B, G) :- A < B, N is B-A, gcd(A, N, G).
```