Part IB, Part II(General) and Diploma

# Comparative Programming Languages

by

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## The Course

- This is a fairly new course.
- It will cover language design issues of a variety of programming languages.
- It will give thumb nail sketches of several languages.
- Some languages, particularly C and C++, will be covered in slightly nore detail, since any computer scientist should be able to read code in these two.

## Books

- Pratt, T.W. & Zelkowitz, M.V. (1996). *Programming Languages, Design and Implementation*. Prentice-Hall (3rd ed.).
- Appleby, D. & VandeKopple, J.J. (1997). *Programming Languages, Paradigm and Practice*. McGraw-Hill (2nd ed.).
- Stroustrup, B. *The C++ Programming Language*. Addison-Wesley.
- Stroustrup, B. (1994). *The Design and Implementation of C++*. Addison-Wesley.
- Mössenböck, H. (1993). *Object-Oriented Programming in Oberon-2*, Springer-Verlag.

## More Books

- Antonakos, J.L. & Mansfield Jr., K.C. (1998). *Reference Guide to C and C++.* Prentice-Hall.
- Kernighan, B.W. & Ritchie, D.M. (1988). *The C Programming Language.* Prentice-Hall (2nd ed.).
- Banahan, M. *The C Book*, Addison Wesley

## Why Study Programming Languages?

- To improve your ability to develop effective algorithms.
- To improve your use of your existing language.
- To increase your vocabulary of useful programming constructs.
- To allow a better choice of programming language.
- To make it easier to learn a new language.
- To make it easier to design a new language.

## History

**1951-55:** Experimental use of expression compilers.

**1956-60:** FORTRAN, ALGOL 60, COBOL, LISP

**1961-65:** APL notation, ALGOL 60 (revised), SNOBOL, CPL

**1966-70:** APL, SNOBOL 4, FORTRAN 66, SNOBOL 4, BASIC, SIMULA 67, ALGOL 68, ALGOL-W, BCPL

## History

**1971-75:** Pascal, PL/1 (Standard), C, Scheme, Prolog

**1976-80:** Smalltalk, Ada, FORTRAN 77, ML

**1981-85:** Smalltalk-80, Growth of Prolog, Ada 83

**1986-90:** C++, SML

**1991-95:** Ada 95, TCL, Perl

**1996-00:** Java

## Changing Influences

- Computer capabilities.
- Applications.
- Programming methods.
- Implementation methods
- Theoretical studies.
- Standardisation.

## What makes a good language

- Clarity, simplicity, and unity.
- Orthogonality.
- Naturalness for the application.
- Support of abstraction.
- Ease of program verification.
- Programming environments.

## What makes a good language

- Portability of programs.
- Cost of use.
  - Cost of execution.
  - Cost of program translation.
  - Cost of program creation, testing, and use.
  - Cost of program maintenance.

## Application Domains

- Business processing.
- Scientific.
- System.
- AI.
- Publishing.
- Process control
- Embedded systems.
- New paradigms.

## Language Standardisation

```
int i; i = (1 && 2) + 3;
```

Is it valid C and what is the value of `i`?

How do we answer such questions?

1. Read the reference manual.
2. Try it and see!
3. Read the ANSI C Standard.

## Language Standards

- Proprietry standards
- Consensus standards.
  - ANSI.
  - IEEE.
  - BSI.
  - ISO.

## Language Standards

- Timeliness.
- Conformance.
- Obsolescence.
- Ambiguity and freedom to optimise.
- Machine dependence.
- Undefined.
- Deprecated.

## Language Standards

What does the following mean?

```
x = y + z;

x = z + y;

x = a + b + c;

x = (a + b) + c;

x = a + (b + c);

a = a + b + c;

b = a + b + c;
```

## Language Standards

What does the following mean?

```
x = x + g()
```

```
x = g() + x;
```

```
x = g() + g();
```

## Language Standards

What does the following mean?

```
int x=1, y=1;

int g() { return ++y; }

int main() {
  x = ++x + ++x;
  y = g() + g();
  printf("x=%d y=%d\n", x, y);
  return 0;
}
```

Answer:

```
Linux               (gcc):   x=6 y=5
Mips                (gcc):   x=5 y=5
                    (cc):    x=6 y=5
DEC Alpha and Sun4  (gcc):   x=5 y=5
                    (cc):    x=5 y=5
```

## Language Standards - PL/1

What does the following mean?

```
9 + 8/3
```

Is it?

1. 11.6666666....
2. Overflow
3. 1.6666666....

What does the following mean?

```
IF (1=1B) THEN ...
```

## Language Standards - PL/1

`DEC(p,q)` means `p` digits with `q` are after the decimal point.

Type rules for DECIMAL in PL/1:

```
DEC(p1,q1) + DEC(p2,q2) =>
  DEC(1+MAX(p1-q1,p2-q2)+MAX(q1,q2),MAX(q1,q2))
DEC(p1,q1) / DEC(p2, q2) =>
  DEC(15, 15-((p1-q1)+q2))
```

So, for `9 + 8/3`, we have:

```
     DEC(1,0) + DEC(1,0)/DEC(1,0)
=>   DEC(1,0) + DEC(15, (15-((1-0)+0)))
=>   DEC(1,0) + DEC(15,14)
=>   DEC(1+MAX(1-0,15-14)+MAX(0,14), MAX(0,14))
=>   DEC(15,14)
```

So the calculation is as follows:

```
  9 + 8/3
= 9 + 2.66666666666666
=    11.66666666666666  -- OVERFLOW
=     1.66666666666666  -- OVERFLOW disabled
```

## Language Standards - PL/1

Evaluation of: `IF (1=1B) ...`

```
      1   =   1B  -- DEC(1,0) and BIT STRING
=>   0001B = 1000B -- two BIT STRINGs
=>          0        -- FALSE
```

## FORTRAN History

- The first high level language to become widely used.
- First developed by IBM for the IBM 704 computer in 1957.
- Emphesis on efficiency (for that machine).
- Static storage allocation and no recursion.
- Standards in 1966, 1977 and 1990.

## FORTRAN

```
PROGRAM TRIVIAL
INTEGER I
I=2
IF(I .GE. 2) CALL PRINTIT
STOP
END
SUBROUTINE PRINTIT
PRINT *,'Hello World'
RETURN
END
```

## FORTRAN 77

```
      PROGRAM MAIN
      PARAMETER (MAXSIZ=99)
      REAL A(MAXSIZ)
 10   READ (5,100,END=999) K
100   FORMAT(I5)
        IF (K.LE.0.OR. K.GT.MAXSIZ) STOP
        READ *,(A(I),I=1,K)
        PRINT *,(A(I),I=1,K)
        PRINT *,'SUM=',SUM(A,K)
        GOTO 10
999   PRINT *,'All Done'
      STOP
      END
```

## FORTRAN 77

```
C  SUMMATION PROGRAM
      FUNCTION SUM(V,N)
      REAL :: V(N) ! New style declaration
      SUM = 0.0
      DO 20 I = 1,N
        SUM = SUM + V(I)
20      CONTINUE
      RETURN
      END
```

## Features

- Static storage.
- No recursion (in FORTRAN 66), so no runtime stack needed.
- Separate compilation – extensive numerical libraries, e.g. NAG.
- Shared COMMON data areas.
- The EQUIVALENCE statement.
- Subroutine arguments passed by reference.
- Efficient compiled code.
- Extensively used for scientific work.
- Archaic syntax.

## COBOL History

- COBOL (COmmon Business Oriented Language) has been widely used since the early 1960s.
- First version in 1960, revisions in 1974 and 1984.
- Uses nouns and verbs to describe actions.
- Complete separation of data descriptions from commands.
- Compilers used to be complex and slow.
- Programs somewhat easier to read than to write.
- Often blamed for the Y2K problem!

## COBOL Example

```
IDENTIFICATION DIVISION
PROGRAM-ID. SUM-OF-PRICES.
AUTHOR. T-PRATT.
ENVIRONMENT DIVISION.
CONFIGURATION SECTION.
SOURCE-COMPUTER. SUN.
OBJECT-COMPUTER. SUN.
INPUT-OUTPUT SECTION.
FILE-CONTROL.
    SELECT INP-DATA ASSIGN TO INPUT.
    SELECT RESULT-FILE ASSIGN TO OUTPUT.
DATA DIVISION.
FD INP-DATA LABEL RECORD IS OMITTED.
01 ITEM-PRICE.
    02 ITEM PICTURE X(30)
    02 PRICE PICTURE 9999V99.
WORKING-STORAGE SECTION.
77 TOT PICTURE 9999V99, VALUE 0, USAGE COMPUTATIONAL.
01 SUM-LINE.
    02 FILLER VALUE ' SUM =' PICTURE X(12).
    02 SUM-OUT PICTURE $$,$$$,$$9.99.
    02 COUNT-OUT PICTURE ZZZ9.
    ... More data
```

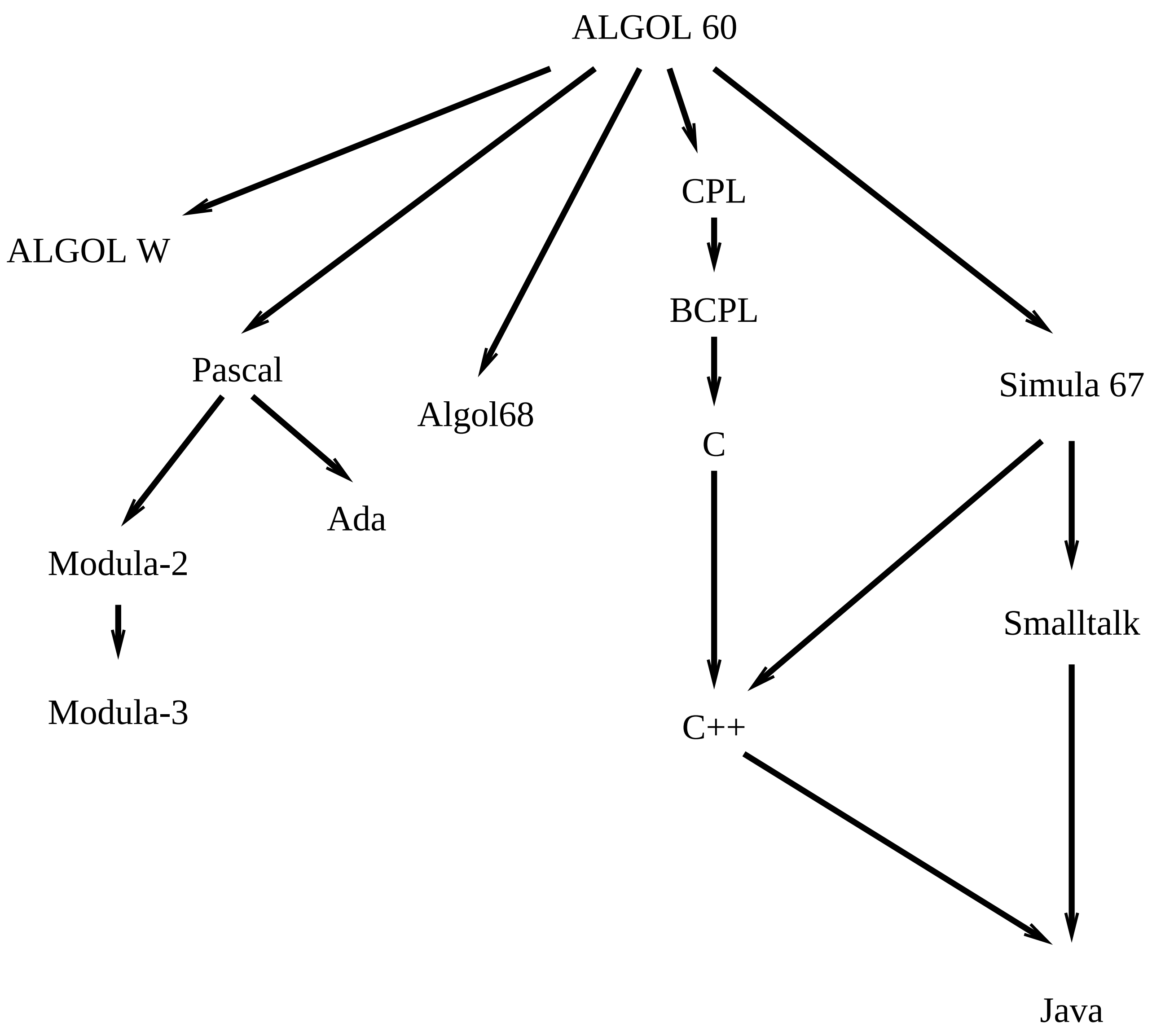
## COBOL (Cont)

```
PROCEDURE DIVISION.
START.
    OPEN INPUT INP-DATA AND OUTPUT RESULT-FILE.
READ-DATA.
    READ INP-DATA AT END GO TO PRINT-LINE.
    ADD PRICE TO TOT.
    ADD 1 TO COUNT.
    MOVE PRICE TO PRICE-OUT.
    MOVE ITEM TO ITEM-OUT.
    WRITE RESULT-LINE FROM ITEM-LINE.
    GO TO READ-DATA.
PRINT-LINE.
    MOVE TOT TO SUM-TOT.
    ... More statements
    CLOSE INP-DATA AND RESULT-FILE.
    STOP RUN.
```

## COBOL

- Data often held in a form that requires little conversion during input/output.
- Arithmetic operations simple and less important than data movement.
- Static data allocation and no recursion.
- Originally the only subroutine mechanism was the PERFORM statement which allowed specified paragraphs to be executed, possibly repeated.
- Such subroutines were parameterless.

## ALGOL Influence



## ALGOL History

- Designed by a committee in 1958
- ALGOL 60 (1960), Revised (Rome 1962)
- Eclipsed by FORTRAN because
  - No I/O statements.
  - No separate compilation.
  - No library.
  - Not supported by IBM.
- But had a major effect on language design.

## ALGOL Innovations

- Block structure.
- Explicit type declarations for variables.
- Scope rules for local variables.
- Dynamic (not static) lifetimes for variables.
- Nested if-then-else expressions and statements.
- Call-by-value and call-by-name arguments.
- Recursive subroutines.
- Arrays with dynamic bounds.
- Use of BNF syntax description.

## ALGOL Example

```
comment  The following procedure
         will transpose a square matrix;

procedure transpose(A, m)
  value m;
  real array A; integer m;
begin integer i, k;
  for i := 1 step 1 until m do
    for k := i+1 step 1 until m do
      begin real w;
            w := A[i,k];
            a[i,k] := a[k,i];
            a[k,i] := w
      end
end transpose
```

## Call by name

```
real procedure sum(E, i, low, high)
  value low, high; real E;
  integer i, low, high;
begin sum := 0.0;
  for i := low step 1 until high do
    sum := sum + E;
end
...
integer j;
real array A[1:10];
real result;
for j := 1 step 1 until 10 do A[j] := j;

result :=  sum(A[j], j, 1, 10)
```

## Call by name

The call:

```
sum(A[j], j, 1, 10)
```

is equivalent to:

```
begin sum := 0.0;
  for j := 1 step 1 until 10 do
    sum := sum + A[j];
end
```

## Nested Procedures

```
integer procedure f(n);
  integer n;
begin
  integer a;

  integer procedure g(m);
    integer m;
  begin g := n + a + m;
        a := a+1
  end;

  if n=0 then a := 0;

  f := g(a)
end
```

## Trouble spots 1

11 different possible answers to:

```
begin
  integer a;

  integer procedure f(x, y);
      value x, y;
      integer x, y;
    a := f := x+1;

  integer procedure g(x);
      integer x;
    x := g := a+2;



  a := 2;
  outreal(1, a + f(a, g(a))/g(a))
end
```

## Trouble spots 2

- The types and mode of calling of procedure arguments could not be specified.
- The goto statement could cause a jump out to a label outside the current procedure.
- Labels were numeric (as in FORTRAN) and could be muddled with integers when passed in function arguments.
- Automatic type conversions were not fully specified, for example `x := x/y` was not properly defined when `x` and `y` were integers. (Is it allowed, and if so was `x` rounded or truncated.
- Own variables were a disaster.
- No precision specified for real numbers.

## ALGOL W

- Designed by Niklaus Wirth (about 1968).
- More pragmatic with repect to efficiency.
- One of the first languages to have structures in the form of records with named fields.
- Allowed pointers to records.
- It had four modes of calling procedure arguments.

## ALGOL W Arguments

```
PROCEDURE SUB1(INTEGER A;
               INTEGER VALUE B;
               INTEGER RESULT C;
               INTEGER VALUE RESULT D);
BEGIN
      B:= 7;
      A:=A+B;
      C:=B+D;
      D:=5
END
```

## ALGOL W Arguments

```
PROCEDURE SUB1(INTEGER A;
               INTEGER B;
               INTEGER C;
               INTEGER D);
BEGIN
      INTEGER BB;
      INTEGER CC;
      INTEGER DD;
      BB:=B;
      DD:=D;

      BB:= 7;
      A:=A+BB;
      CC:=BB+DD;
      DD:=5;

      C:=CC;
      D:=DD
END
```

## ALGOL W Records

```
RECORD CARD (INTEGER VAL;
             INTEGER SUIT);
RECORD HAND (REFERENCE(CARD) CARD;
             REFERENCE(HAND) NEXT);

REFERENCE(HAND) NORTH;

NORTH := HAND(CARD(1,1),
         HAND(CARD(12,1),NULL));

... VAL(CARD(NEXT(NORTH))) ...
```

## ALGOL W Problems

What does `X(Y)` mean?

It depends on the types of `X` and `Y`.

It could be:

- An array subscription.
- A procedure call.
- A field selection.
- A record constructor application.

Unfortunately, since formal procedures do not have their argument types specified, the types of variable are not always known.

## BCPL

An implementation is available on thor. If you would like to try it, look at `README.thor` in directory:

`http://www.cl.cam.ac.uk/~mr`

It is also available via my Home Page:

`http://www.cl.cam.ac.uk/~mr`

## BCPL History

- It was designed and implemented in early 1967 when I was at at MIT.
- It is a very cut down version of CPL(1962-68) that is easy to implement.
- It was used extensively for systems research, particularly for the development of the Tripos Operating System and early developments of the Cambridge Ring.
- It is still used as a testbed for compiler research.

## BCPL Summary

- It was designed as a systems programming language suitable for writing compilers and operating systems.
- It is typeless. All values are the same size (typically 32 bits).
- Values can be used to represent characters, integers, truth values, and pointers to data or code.
- Any operation is allowed on any value even though the result is sometimes meaningless.

## BCPL Summary

- Pointers can be used to represent:
  - character strings,
  - vectors,
  - structures,
  - functions and
  - program labels.
- Memory was modelled as a collection of equal sized words, addressed by consecutive integers. This allows machine independent pointer arithmetic.

## BCPL Example

```
GET "libhdr"

LET f(n) = n=0 -> 1, n*f(n-1)

LET start() = VALOF
{ FOR i = 1 TO 9 DO
    writef("f(%n) = %i5*n", i, f(i))
  RESULTIS 0
}
```

## BCPL Functions

- Function arguments are called by value and stored in consecutive memory locations.
- Functions are variadic (allow a variable number of arguments, as in `writef`).
- Functions may be passed as arguments, returned as results, or assigned.
- Although function definitions may be nested, they may not contain variables referring to either arguments or locals of enclosing functions.
- Functions can be be correctly represented by just their entry addresses.
- Separate compilation was allowed using the global vector for inter module referencing.

## BCPL Example

```
GET "libhdr"

GLOBAL { count:200; all:201  }

LET try(ld, row, rd) BE
  TEST row=all
  THEN count := count + 1
  ELSE { LET poss = all & ~(ld | row | rd)
         UNTIL poss=0 DO
         { LET p = poss & -poss
           poss := poss - p
           try(ld+p << 1, row+p, rd+p >> 1)
         }
       }

LET start() = VALOF
{ all := 1

  FOR i = 1 TO 12 DO
  { count := 0
    try(0, 0, 0)
    writef("%i2-queens solutions %i5*n",
            i,                    count)
    all := 2*all + 1
  }

  RESULTIS 0
}
```

## BCPL Example

```
GET "libhdr"

LET coins(sum) = c(sum, (TABLE 50, 20, 10, 5, 2, 1))

AND c(sum, t) = sum<0 -> 0,
                sum=0 | !t=1 -> 1,
                c(sum, t+1) + c(sum-!t, t)

LET start() = VALOF
{  writes("Coins problem*n")

   t(0)
   t(1)
   t(2)
   t(5)
   t(21)
   t(100)
   t(200)
   RESULTIS 0
}

AND t(n) BE
  writef("Sum = %i3  number of ways = %i6*n",
                n,                 coins(n))
```

## BCPL Memory

| Address | Contents |
|---|---|
| 1000: | 13 |
| 1001: | 2000 |
| 1002: | 0 |
| ... | |
| 2000: | 61 |
| 2001: | 0 |
| 2002: | 24 |

The expression: `1000!1!2` evaluates as follows:

```
       1000 ! 1 ! 2
=     (!(1000+1)) ! 2
=     (!(1001)) ! 2
=       2000 ! 2
=       !(2000+2)
=       !2002
=       24
```

## BCPL Streams

```
LET next(s) = (s!0)(s)

LET out(s, x) = (s!1)(s, x)

LET close(s) = (s!2)(s)
```

The functions `s!0`, `s!1`, `s!2` are analogous to methods of the object `s` in an object oriented language.

The functions defined above were used by Christopher Strachey in the operating system OS/6 in 1970.

## BCPL Objects

In an object oriented language, classes have fields and methods.

Often the fields hold different values for different instances of a class, but the methods are usually the same for each instance.

This suggests an implementation in which the methods are held in a vector (of method functions) which is referenced by each instance of the class.

The fields vector must be accessible to each method and so is normally passed as a (hidden) extra argument in a method call.

## BCPL Objects

The following scheme works well for BCPL.

In the scope of the declaration:

```
MANIFEST { F=0; G=1; H=2 }
```

The expression

```
                G#(obj, 13, 63)
```

means:

```
           (obj!0!G)(obj, 13, 63)
            (fns!1) (obj, 13, 63)
            methodG (obj, 13, 63)


obj -> 0:  fns -------------> 0: methodF
       1: FieldA              1: methodG
       2: FieldB              2: methodH
          ...
       n: FieldZ
```

## BCPL Coroutines

Coroutines are somewhat like threads (or processes).

- They simulate parallel execution.
- They share the same address space.
- But they only giveup control voluntarily (no pre-emption).

Each coroutine needs its own runtime stack.

When control passes from one BCPL coroutine to another, a value is passed.

This value looks like an argument in the coroutine than is suspending itself, and like a result in the coroutine that is resuming control.

## BCPL Coroutines

The implementation is as follows:

```
  --------------------->------------------
 |                                       |
 ---------------------------------------------------------
|p  parent nxt  f  size  c  | .. stack .. suspended frame ..
 ---------------------------------------------------------
 |    |     |   |   |    |
 |    |     |   |   |    System work variable
 |    |     |   |   Size of the coroutine stack
 |    |     |   Coroutine main function
 |    |     Next coroutine
 |    The parent coroutine
 The save stack frame pointer
```

```
cptr := createco(f, size)   -- Create a coroutine.
deleteco(cptr)              -- Delete a coroutine.
res := callco(cptr, val)    -- Call another coroutine (cptr).
res := cowait(val)          -- Transfer control to the parent.
res := resumeco(cptr, val)  -- Suspend the current coroutine
                               and transfer to another.
```

The body of a coroutine behaves like:

```
   c := f(cowait(c))    // Repeat for ever
   REPEAT
```

## Coroutines Example

```
GET "libhdr"

MANIFEST { upb = 4000 }

LET prime1() = VALOF

{ LET isprime = getvec(upb)
  FOR i = 2 TO upb DO
    isprime!i := TRUE // Until disproved
  FOR p = 2 TO upb IF isprime!p DO
  { LET i = p*p
    UNTIL i>upb DO
    { isprime!i := FALSE; i := i + p }
    cowait(p)
  }
  freevec(isprime)
  RESULTIS 0
}

AND prime2() = VALOF
{ FOR n = 2 TO upb DO
  { LET a, b = 2, 1
    FOR i = 1 TO n DO
    { LET c = (a+b) REM n; a := b; b := c }
    IF a=1 DO cowait(n)
  }
  RESULTIS 0
}
```

## Coroutines Example

```
LET start() = VALOF
{ LET P1 = createco(prime1, 100)
  LET P2 = createco(prime2, 100)
  LET n1, n2, min = 0, 0, 0
  { IF n1=min DO n1 := callco(P1)
    IF n2=min DO n2 := callco(P2)
    min := n1<n2 -> n1, n2
    UNLESS n1=n2 DO
      writef(" %i4 from P%c*n", min, n1<n2 -> '1', '2')
  } REPEATUNTIL min=0
  deleteco(P1)
  deleteco(P2)
  RESULTIS 0
}
```

## C History

- Designed by Dennis Ritchie and Ken Thompson at Bell Labs in 1972.
- It was based in B, a squeezed down minimal subset of BCPL implemented on an 8K PDP-7 by Ken Thompson.
- In 1970 the Unix project acquired a 24K PDP-11 and B was expanded to include structures and a more operators. This language became known as C.
- It was first used to write the kernel of Unix and has been closely associated with Unix ever since.
- ANSI Standard (1989)
- ISO Standard (1990)

## C Example

```
#include <stdio.h>

const int maxsize=9;

int convert(char ch) { return ch-'0'; }

int sum(int v[], int n) {
  int res=0;
  int j;
  for(j=0; j<n; j++) res+=v[j];
  return res;
}

int main() {
  int a[maxsize];
  int j, k;
  while(k=convert(getchar())) {
    for(j=0; j<k; j++) a[j]=convert(getchar());
    for(j=0; j<k; j++) printf("%d ", a[j]);
    printf("; SUM=%d\n", sum(a, k));
    while(getchar() != '\n');
  }
  return 0;
}
```

## Compiling and Running

```
clove$ cc -o example example.c
clove$ example
41234
1 2 3 4 ; SUM 10
512345
1 2 3 4 5 ; SUM 15
0
clove$
```

## C Primitive Types

Numeric types:

```
unsigned char
unsigned short
unsigned int
unsigned long
char
short
int
long

float
double
long double
```

## C Primitive Types

Numeric constants:

```
'A'             -- int
123U            -- unsigned int
1234567890UL    -- unsigned long

123             -- int
0xFF0037        -- int
1234567890L     -- long


123.456F        -- float
123.456         -- double
123.456e-5      -- double
123.456E12      -- double
123.456L        -- long double
```

## Monadic Expression Operators

```
e(e,e,...,e)    -- function call
e[e,e,...,e]    -- subscripted expression
e->name         -- structure selector
e.name          -- field selector

!e              -- boolean not
~e              -- bitwise not
++e    e++      -- pre/post increment
--e    e--      -- pre/post decrement
+e              -- monadic plus
-e              -- monadic minus
(type)e         -- cast (or type conversion)
*e              -- indirection
&e              -- address of
sizeof e        -- size of the given value
```

## Infixed Expression Operators

```
e * e           -- multiplication
e / e           -- division
e % e           -- remainder
e + e           -- plus
e - e           -- minus

e << e          -- left shift
e >> e          -- right shift
```

## Infixed Expression Operators

```
e<e   e>e   e<=e   e>=e     -- relations
e==e  e!=e                  -- relations

e & e             -- bitwize and
e ^ e             -- bitwize xor
e | e             -- bitwize or
e && e            -- boolean and
e || e            -- boolean or
e ? e : e         -- conditional expression
e=e   e+=e ...    -- assignments
e,e,...,e         -- expression list
```

## Statements

```
{ d d ... d s s ... s }  -- a block
e;
;
if (e) s
if (e) s else s
if (e) s else s
while (e) s
do s while(e);
for(e;e;e)s  -- eg for(i=0;i<k;i++)v[i]=0;
switch(e) { case k: s
            ...
            case k: s
            default: s
          }
break;
continue;
return e;
goto name;
name: s
```

## Declarations

```
int i, j=1, k;
float x;
long a, b;

char v[10];
int w[4] = { 0, 1, 2, 3};

int *p, **q;
int * tab[256];    -- vector of pointers

int f(int,int);    -- function declaration
int (*f)(int,int); -- pointer to a function
```

## Casts

| declaration | cast |
|---|---|
| `unsigned int i;` | `(unsigned int)` |
| `float x;` | `(float)` |
| `char v[10];` | `(char [10])` |
| `int w[4];` | `(int [4])` |
| `int *p;` | `(int *)` |
| `int **q;` | `(int **)` |
| `int * tab[256];` | `(int *[256])` |
| `int f(int,int);` | `(int(int,int))` |
| `int (*f)(int,int);` | `(int (*)(int,int))` |
| `void (*g)(void);` | `(void(*)(void))` |

## Functions

Declarations, eg:

```
/* a declaration  */
int mymax(int, int);
```

Definitions, eg:

```
/* a definition */
int mymax3(int a, int b, int c) {
  return mymax(a, mymax(b, c));
}

/* another definition */
int mymax(int a, int b) {
  return a>b ? a : b;
}
```

## Arrays and Pointers

```
int a[20], *p;

p = & a[5];
*p = 0;  /* equivalent to a[5] = 0;  */

for (p=&a[0]; p<&a[20]; p++) *p = 0;
```

In older compilers the above is more efficient than:

```
int a[20], i;

for (i=0; i<20; i++) a[i]=0;
```

## Pointer Arithmetic

An integer may be added to a pointer. It returns a pointer to the adjacent location of the appropriate size.

If `p` points to a 32 bit integer on a byte addressed machine, then `p+1` or `1+p` points to the adjacent 32 bit integer. In machine code terms this typically involves adding 4 to the byte address held in `p`.

```
  C                     BCPL

int a[20];              LET a = VEC 19
int *p;                 LET p = ?

a[1]                    a!1
*(a+1)                  !(a+1)
*(1+a)                  !(1+a)
1[a]                    1!a
&a[1]                   @ a!1
& *(a+1)                @ !(a+1)
a+1                     a+1
```

## Strings

C character strings are zero terminated char vectors. BCPL strings are byte vectors with the length held in byte zero.

```
  C                         BCPL

char s[5]="ABCD";           LET s = "ABCD"


s[0] == 'A'                 s%0 =  4
s[1] == 'B'                 s%1 = 'A'
s[2] == 'C'                 s%2 = 'B'
s[3] == 'D'                 s%3 = 'C'
s[4] ==  0                  s%4 = 'D'
```

## String Copying

C:

```
void copystring(char *from, char *to) {
  while (*from) *to++ = *from++;
  *to=0;
}
```

BCPL:

```
LET copystring(from, to) BE
  FOR i = 0 TO from%0 DO to%i := from%i
```

## Space Allocation

C:

```
int *p = (int *)malloc(sizeof(int[100]));
if(p==0) .... /* no space  */
...
free(p);
```

BCPL:

```
LET p = getvec(99)
IF p=0 DO  ... // no space
...
freevec(p)
```

## Structures

```
#include <stdio.h>

struct Inode {
  int val;
  struct Inode* next;
} *p, *q;

struct Inode *mk(int x, struct Inode *rest) {
  struct Inode *res =
   (struct Inode*)malloc(sizeof(struct Inode));
  res->val = x;
  res->next = rest;
  return res;
}

int main(int argc, char** argv) {
  p = mk(13, 0);
  q = mk(541, p);
  printf("%d\n", q->next->val);
  return 0;
}
```

## Structures

```
#include <stdio.h>

typedef struct Inode {
  int val;
  struct Inode *next;
} *Ilist;

Ilist mk(int x, Ilist rest) {
  Ilist res = (Ilist)malloc(sizeof(struct Inode));
  res->val = x;
  res->next = rest;
  return res;
}

int main(int argc, char** argv) {
  Ilist p = mk(13, 0);
  Ilist q = mk(541, p);
  printf("%d\n", q->next->val);
  return 0;
}
```

## Structures

```
#include <stdio.h>

typedef struct Inode Inode;

struct Inode {
  int val;
  Inode *next;
};

Inode *mk(int x, Inode *rest) {
  Inode *res = (Inode *)malloc(sizeof(Inode));
  res->val = x;
  res->next = rest;
  return res;
}

int main(int argc, char** argv) {
  Inode *p = mk(13, 0);
  Inode *q = mk(541, p);
  printf("%d\n", q->next->val);
  return 0;
}
```

## Field Selection

The field selection operator is dor (.) as in Java. The arrow notation is a shortcut for indirection followed by field selection.

`e -> name` means `(* e) . name`.

## Unions

Sometimes it is useful to have a variable whose value is one type at one moment and another type later. This is possible using unions.

Syntactically a union declaration is just like a structure declaration, only the `struct` is replaced by `union`.

It causes all the fields to be overlaid at the same position, rather than being given distinct locations.

## Unions

```
union {
  float f;
  int i;
} var;

var.f = 23.5
printf("val = %f\n", var.f);

var.i = 5
printf("val = %d\n", var.i);
```

## Example Problem

Construct a tree representation suitable for the expressions like `1+2*3`, and define a function `eval` to evaluate it.

The required structure is something like:

```
    ADD
   /   \
  /     \
NUM     MUL
 1     /   \
      /     \
    NUM     NUM
     2       3
```

## ML Solution

```
datatype E = NUM of int
           | POS of E
           | NEG of E
           | MUL of E * E
           | DIV of E * E
           | ADD of E * E
           | SUB of E * E;

fun eval(NUM k)     = k
  | eval(POS e)     = eval e
  | eval(NEG e)     = ~ (eval e)
  | eval(MUL(x,y)) = eval x   *  eval y
  | eval(DIV(x,y)) = eval x div eval y
  | eval(ADD(x,y)) = eval x   +  eval y
  | eval(SUB(x,y)) = eval x   -  eval y;

eval( ADD(NUM 1,
          MUL(NUM 2, NUM 3)));
```

## BCPL Solution

```
GET "libhdr"

MANIFEST {
Op=0; Rand1=1; Rand2=2
NUM=1; POS=2; NEG=3; MUL=4; DIV=5; ADD=6; SUB=7
}

LET eval(e) = VALOF SWITCHON Op!e INTO
{ CASE NUM: RESULTIS Rand1!e
  CASE POS:  RESULTIS + eval(Rand1!e)
  CASE NEG:  RESULTIS - eval(Rand1!e)
  CASE MUL:  RESULTIS eval(Rand1!e) * eval(Rand2!e)
  CASE DIV:  RESULTIS eval(Rand1!e) / eval(Rand2!e)
  CASE ADD:  RESULTIS eval(Rand1!e) + eval(Rand2!e)
  CASE SUB:  RESULTIS eval(Rand1!e) - eval(Rand2!e)
}
```

## BCPL Solution

```
LET mk1(op, a) = VALOF
{ LET r = getvec(1)
  Op!r, Rand1!r := op, a
  RESULTIS r
}

LET mk2(op, a, b) = VALOF
{ LET r = getvec(2)
  Op!r, Rand1!r, Rand2!r := op, a, b
  RESULTIS r
}

LET start() = VALOF
{ LET exp = mk2(ADD, mk1(NUM, 1),
                     mk2(MUL, mk1(NUM,2), mk1(NUM,3)))
  writef("eval(exp) = %n*n", eval(exp))
  RESULTIS 0
}
```

## MCPL Solution

```
GET "mcpl.h"

MANIFEST
NUM, POS, NEG, MUL, DIV, ADD, SUB

FUN eval
: [NUM, val]    => val
: [POS,   x]    => + eval x
: [NEG,   x]    => - eval x
: [MUL,   x, y] => eval x * eval y
: [DIV,   x, y] => eval x / eval y
: [ADD,   x, y] => eval x + eval y
: [SUB,   x, y] => eval x - eval y

FUN start : =>
  printf("val = %d\n",
          [ADD,[NUM,1],[MUL,[NUM,2],[NUM,3]]]
        )
```

## Union Example

```
#include <stdio.h>

enum Ops {NUM, POS, NEG, MUL, DIV, ADD, SUB};

typedef struct Num Num;
typedef struct Monad Monad;
typedef struct Dyad Dyad;

typedef union Expr {
  Num *N;
  Monad *M;
  Dyad  *D;
} Expr;

struct Num {
  int op;
  int val;
};

struct Monad {
  int op;
  Expr rand;
};

struct Dyad {
  int op;
  Expr left;
  Expr right;
};
```

## Union Example

```
Expr mknum(int n) {
  Expr res;
  Num *e = (Num *) malloc(sizeof(Num));
  e->op = NUM;
  e->val = n;
  res.N = e;
  return res;
}

Expr mk1(int operator, Expr a) {
  Expr res;
  Monad *e = (Monad *) malloc(sizeof(Monad));
  e->op = operator;
  e->rand = a;
  res.M = e;
  return res;
}

Expr mk2(int operator, Expr a, Expr b) {
  Expr res;
  Dyad *e = (Dyad *) malloc(sizeof(Dyad));
  e->op = operator;
  e->left = a;
  e->right = b;
  res.D = e;
  return res;
}
```

## Union Example

```
int eval(Expr e) {
  switch(e.M->op)
  { default:  return 0;

    case NUM: return e.N->val;
    case POS: return eval(e.M->rand);
    case NEG: return - eval(e.M->rand);
    case MUL: return eval(e.D->left) * eval(e.D->right);
    case DIV: return eval(e.D->left) / eval(e.D->right);
    case ADD: return eval(e.D->left) + eval(e.D->right);
    case SUB: return eval(e.D->left) - eval(e.D->right);
  }
  return 0;
}

int main() {
  Expr exp = mk2(ADD,
                 mknum(1),
                 mk2(MUL, mknum(2), mknum(3)));
  printf("eval(exp) => %d\n", eval(exp));
}
```

## Object Oriented Languages

Object Oriented Languages support:

- Data abstraction (the encapsulation of state with operations).
- Information hiding (encapsulation).
- Message passing and polymorphism.
- Inheritance, including dynamic binding.

Significant languages in the history of Object Orientation.

- Simula-67
- Smalltalk
- C++
- Java
- Oberon, Eiffel and many others

## Simula-67

- Originated in Norway by Nygaard and Dahl in 1961, and was fully developed by 1967.
- Based on Algol 60.
- Designed for discrete event simulation.
- It extended Algol to contain objects that had state and a thread of control (similar to coroutine) that could simulate parallel activities.
- It had an inheritance mechanism.

## Simula-67 Example

A simulation of a post office with a door, 4 counters, each with a clerk and a queue, and a random supplied of customers entering the door.

## Simula-67 Example

```
BEGIN

CLASS customer(tasks, oldlady)
  INTEGER tasks; BOOLEAN oldlady;     BEGIN ... END;

CLASS queue;                          BEGIN ... END;

CLASS clerk(q); ref(queue)q;          BEGIN ... END;

CLASS door;                           BEGIN ... END;

CLASS counter;                        BEGIN ... END;

REAL opentime, closetime;
REF(counter) c1, c2, c3, c4;

opentime := 8.00;
closetime := 17.00;

hold(opentime);
c1 :- NEW counter;
c2 :- NEW counter;
c3 :- NEW counter;
c4 :- NEW counter;
NEW door;

hold(closetime);
END
```

## Simula-67 Example

```
CLASS customer(tasks, oldlady)
  INTEGER tasks; BOOLEAN oldlady;
BEGIN
  REF(customer) next;
  REF(counter) service;

  WHILE tasks>0 DO
  BEGIN
    <assign value to service>;
    IF oldlady THEN <enter front of service.q>
               ELSE <enter tail of service.q>;
    IF service.postofficer is free
    THEN <activate service.postofficer>
    ELSE passivate;
    <participate in transaction>;
    <leave counter>
    tasks := tasks-1;
  END
END;
```

## Simula-67 Example

```
CLASS queue;
BEGIN
  REF(customer) first, last;
END;


CLASS clerk(q); REF(queue)q;
BEGIN
  REF(customer) person;
seviceing:
  WHILE q.first =/= NONE DO
  BEGIN person :- q.first;
        <take person out of the queue>;
        <engage with him in transactions>;
  END;
  <do other work until interrupted by the
   arrival of a new customer in the queue>;
  GOTO servicing;
END;
```

## Simula-67 Example

```
CLASS door;
BEGIN
  REAL arrtime;

  WHILE time<=closetime DO
  BEGIN arrtime := <time of next arrival>;
        hold(arrtime);
        NEW customer(<initial value of tasks>,
                     <initial value of oldlady>);
  END;
END;
```

```
CLASS counter;
BEGIN
  REF(queue) q;
  REF(clerk) postofficer;

  q :- NEW queue;
  postofficer :- NEW clerk(q);
END;
```

## Simula-67 Class Hierachy

A hierachy of classes can be declared.

```
  CLASS a ...;
a CLASS b ...;
a CLASS c ...;
b CLASS d ...;
b CLASS e ...;
```

```
        Hierarchy             Objects


                      a     b     c     d     e
                     ---   ---   ---   ---   ---
            a       | a | | a | | a | | a | | a |
           / \       ---  |---| |---| |---| |---|
          /   \           | b | | c | | b | | b |
         b     c           ---   ---  |---| |---|
        / \                           | d | | e |
       /   \                           ---   ---
      d     e
```

## Simula-67 Various Primitive

Componentes in a simulation which may be scheduled should be prefixed by the class `process`. The class outline is:

```
link CLASS process;
BEGIN BOOLEAN PROCEDURE idle; ...;
      REAL PROCEDURE evtime; ...;
      REF(process) PROCEDURE nextev; ...;
      detach;
      ...
      passivate;
END;
```

## Simula-67 Various Primitive

```
REF(process) PROCEDURE current; ...
```

returns the current process.

```
REAL PROCEDURE time; ...
```

returns the current time.

```
PROCEDURE hold(t); REAL t; ...
```

suspend the current process until time `t`..

```
PROCEDURE cancel(p); REF(process) p; ...
```

remove p from the event queue.

```
ACTIVATE p;
ACTIVATE p AT time;
ACTIVATE p DELAY time;
```

activate `p` at specified time.

## Smalltalk

Smalltalk was designed by Alan Kay in 1972 when he was working at Xerox PARC (Palo Alto) as part of his Dynabook project.

It was influenced by some of Papert's work at MIT on Logo, an interactive highly graphical computer learning environment intended to teach programming to children.

Dynabook was a far sighted early version of a handheld computer.

The first was made of cardboard and filled with lead shot, to see what size and weight people would put up with.

## Smalltalk

Smalltalk was designed an an interpretive language, in which all names were looked up at runtime from and environment of declared names.

In more modern implementations code is compiled giving a speedup of 450 times!

There are several Smalltalk implementations including a GNU version and one from the Disney Corporation (where Alan Kay now works).

This latter one is embedded in a system called Squeek and the version of Smalltalk is called Self.

It consists of a complete program development system that is responsive and small enough (approx 1-2 Mbytes) to fit in a Palm Top or Handheld computer.

## Smalltalk

Smalltalk is a purely object-oriented language which cleanly supports the notions of classes, methods, messages and inheritance.

All smalltalk code consists of chains of messages sent to objects.

Its syntax is almost trivial.

```
BODY -> | name ... name | E . E ... E

E    -> name                         x  Transcript   :=
      | # E                          #green
      | number                       123
      | string                       'hello'
      | ( E )
      | ^ E                          return with value of E
      | [ E . E ... E ]              [Transcript show: 'hello']
      | [ :name ... :name | E . E ... E ]  [: x | x + 1]
      | E name
      | E name E ... name E
      | E name E ... name E ; ... ; name E ...
```

## Smalltalk Fragments

```
|count|
count := 0.
[count < 3]
  whileTrue:
    [ (count odd) ifTrue: [Transcript show: ’ODD’]
                  ifFalse: [Transcript show: ’EVEN’].
       count := count+1.
       Transcript cr.
    ]
```

```
|canon|
canon := [ :singers :song |
           singers do:
             [:voice | Transcript
                         show: voice asString, ’,’, song;
                         cr]]


canon value: #(kermit jasper fred) value: ’croak’.
```

## Smalltalk Class

For programming convenience Smalltalk classes a grouped into Categories and their methods are also grouped into categories.

```
Morphic-Window                 -- Class categories
Graphics-3D
...
Interface-Pluggable
Sesame-Street
   CookieMonster               -- a class
     initialization            -- method categories
     access
     queries
       isAsleep                -- methods
       isAwake
       isFull
           self isEmpty        -- definition of isFull
             ifFalse: [^ self tummy size >= self hunger]
             ifTrue: [^false]
     actions
     private
   Monster                     -- another class
Tools-Outlines
...
```

## Declaring a new Class

A class is created by sending a message to the class that is going to be its parent. For example

```
!Object subclass: #Monster
  instanceVariableNames: 'colour tummy'
  classVariableNames: ' '
  poolDictionaries: ' '
  category: 'Sesame-Street'!
```

This create the class `Monster` which is a subclass of `Object`. It has two instance variables (`colour` and `tummy`) and no class variables, and `Monster` is one of the classes in the category `Sesame-Street`. Ignore `poolDictionaries`.

Classes are created dynamically (during program execution).

## Definition of CookieMonster

We no create a class `CookieMonster` as a subclass of `Monster`. It is also a member of `Sesame-Street`.

```
!Monster subclass: #CookieMonster
  instanceVariableNames: 'state hunger'
  classVariableNames: ' '
  poolDictionaries: ' '
  category: 'Sesame-Street'!
```

## Defining Methods

Methods can be defined by sending a `methodsFor` message to a class. For example:

```
!Monster methodsFor: 'actions'!
eat: someItem
  self tummy add: someItem
!!

!Monster methodsFor: 'queries'!
isEmpty
 ^ self tummy isNil
!!
```

## Defining Methods

```
!Monster methodsFor: 'access'!
colour
 ^ colour
!
colour: aSymbol
 colour := aSymbol
!
tummy
 ^ tummy
!
tummy: aCollection
 tummy := aCollection
!!
!Monster methodsFor: 'initialization'!
initialize
  self colour: #green.
  self tummy: Bag new
!!
```

## Defining Class Methods

Class methods and variables in Smalltalk are like static methods and variables in Java.

There is on class method to define for `Monster`.

```
!Monster class  methodsFor: 'creation'!
new
  ^ super new initialize
!!
```

## Cookie Monster Methods

Cookie Monsters inherit from Monster, but add more specific behaviour of their own.

```
!CookieMonster methodsFor: 'private'!
askForCookie
  ^ FillInTheBlank request: 'Give me a cookie'
!
complainAbout: anItem
  Transcript show: 'No want ', anItem printString.
  Transcript cr.
  self colour #red
!
isCookie: anItem
  ^ ((anItem = 'cookie') | (anItem = #cookie))
!!
```

## Cookie Monster Methods

```
!CookieMonster methodsFor: 'actions'!
eat: aCookie
  super eat: aCookie.
  self colour: #green
!
nag
[self isAwake]
whileTrue:
[| item |
 item := self askForCookie.
 (self isCookie: item)
   ifTrue: [self eat: item]
   ifFalse: [self complainAbout: item].
   (self isFull) ifTrus: [self sleep]
!
sleep
  self state: #asleep.
  self hunger: 0
!
wakeUp
  self tummy: Bag new.
  self state: #awake.
  self hunger: (Random new next * 13).
  self nag.
!!
```

## Cookie Monster Methods

```
!CookieMonster methodsFor: 'queries'!
isAsleep
  ^ state = #asleep
!
isAwake
  ^ self isAsleep not
!
isFull
  self isEmpty
    ifFalse: [^ self tummy size >= self hunger]
    ifTrue: [^false]
!!
!CookieMonster methodsFor: 'access'!
hunger
  ^ hunger
!
hunger: anIntegerNumberOfCookies
  hunger := anIntegerNumberOfCookies
!
state
  ^ state
!!
```

## Object oriented Programming

This lecture covers the paper

What is "Object-Oriented Programming?"
by
Bjarne Stroustrup

It is available via

```
http://www.cl.cam.ac.uk/Teaching
           /2000/CompProgLangs/bjarne.ps
```

## Language Design Philosophy

- All features must be cleanly and elegantly integrated into the language.
- It must be possible to use features in combination to achieve solutions that would otherwise have required extra separate features.
- There should be as few spurious and “special purpose” features as possible.
- A feature should be such that its implematation does not impose significant overheads on programs that do not require it.
- A user need only know about the subset of the language explicitly used to write a program.

## Programming Paradigms

Procedural Programming

```
double sqrt(double arg) {
  // code for calculating a square root
}

void some_function() {
  double root2 = sqrt(2);
  // ...
}
```

## Data Hiding

### The file stack.h

```
char pop();
void push(char);
const stack_size = 100;
```

### The file stack.cpp

```
#include "stack.h"
static char v[stack_size]; // local to module
static char* p = v;

char pop() {
  // check for underflow and pop
}
void push(char ch) {
  // check for overflow and push
}
```

### The file prog.cpp

```
#include "stack.h"

void some_function() {
  push('c');
  char c = pop();
  if (c != 'c') error("impossible");
}
```

## Data Abstraction

### The file stack.h

```
class stack_id; // stack_id is a type

stack_id create_stack(int size);
void destroy_stack(stack_id);
char pop(stack_id);
void push(stack_id, char);
```

### The file prog.cpp

```
#include "stack.h"

void some_function() {
  stack_id s1;
  stack_id s2;
  s1 = create_stack(200);
  // Oops: forgot to create s2
  push(s1, 'a');
  char c1 = pop(s1);
  if (c1 != 'a') error("impossible");
  push(s2, 'b');
  char c2 = pop(s2);
  if (c2 != 'b') error("impossible");
  destroy_stack(s2);
  // Ooops: forgot to destroy s1
}
```

## Data Abstraction

The above scheme is nearly good enough when no more than one object of a type is needed.

```
class complex {
  double re, im;
public:
  complex(double r, double i) { re=r; im=i; }
  complex(double r) { re=r; im=0; }

  friend complex operator+(complex, complex);
  friend complex operator-(complex, complex);
  friend complex operator-(complex);
  friend complex operator*(complex, complex);
  friend complex operator/(complex, complex);
};
```

The definition of `complex +` could be:

```
complex operator+(complex a1, complex a2) {
  return complex(a1.re+a2.re, a1.im+a2.im);
}
```

Typical use:

```
complex a = 2.3;
complex b = 1/a;
complex c = a+b*complex(1, 2.3);
c = - (a/b)+2;
```

## Problems with Data Abstraction

```
class point { ... };
class color { ... };

enum kind { circle, triangle, square };

class shape {
  point center;
  color col;
  kind k;
  // representation of shape
public:
  point where() { return center; }
  void move{point to} { center=to; draw(); }
  void draw();
  void rotate(int);
  // more operations
};

void shape::draw()
  switch (k) {
    case circle:   // draw a circle
                   break;
    case triangle: // draw a triangle
                   break;
    case square:   // draw a square
                   break;
  }
}
```

## Object-Oriented Programming

```
class shape {
  point center;
  color col;
  ...
public:
  point where() { return center; }
  void move{point to} { center=to; draw(); }
  virtual void draw();
  virtual void rotate(int);
  ...
};
```

Typical use of class `shape` is:

```
void rotate_all(shape* v, int size, int angle) {
// rotate all members of a vector by given angle
  for (int i=0; i<size; i++) v[i].rotate(angle);
}
```

Typical definition of a particular shape.

```
class circle : public shape {
  int radius;
public:
  void draw() { ... }
  void rotate() {}  // yes, the null function
}
```

## Initialization and Cleanup

```
class vector {
  int sz;
  int* v;
public:
  void init(int size);
  ...
};


vector v;
// don't use yet
v.init(10);
// ok to use v now
..
```

## Initialization and Cleanup

It is better to use constructors and destructors.

```
class vector {
  int sz;
  int* v;
public:
  vector(int);                  // constructor
  ~vector();                    // destructor
  int& operator[] (int index); // subscript operator
```

Typical definitions:

```
vector::vector(int s) {
  if (s<=0) error("bad vector size");
  sz = s;
  v = new int[s]; // allocate an array
}

vector::~vector() {
  delete v;  // deallocate the vector
}
```

## Assignment and Initialization

It is possible to control all copy operations in C++.

```
class vector {
  int sz;
  int* v;
public:
  vector(int);                  // constructor
  ~vector();                    // destructor
  int& operator[] (int index);  // subscript operator
  void operator=(const vector&); // assignment
  vector(const vector&);        // initialization
};
```

Typical definitions:

```
vector::operator=(const vector& a) {
  // check size and copy elements
  if (sz != a.sz) error("bad vector size for =");
  for (int i=0; i,sz; i++) v[i]=a.v[i];
}

vector::vector(const vector& a) {
  // initialize a vector from another vector
  sz = a.sz;
  v = new int[sz];
  for (int i=0; i,sz; i++) v[i]=a.v[i];
}
```

## Parameterized Types

It would be more useful if the writer of the `vector` class did not know what the element type it is to use.

```
template<class T> class vector { // element type T
  T* v;
  int sz;
public:
  vector(int s) {
    if (s <= 0) error("bad vector size");
    v = new T[sz=s];
  }
  T& operator[] (int index);   // subscript operator
  int size() { return sz; }
  ...
};
```

A template specifies a family of types.

```
vector<int> v1(100);
vector<complex> v2(200);

v2[i] = complex(v1[x], v1[y]);
```

Usually, only one version of `size()` is needed.

## Iterators

Iterators can be provided by overloading the function call operator.

```
class vector_iterator {
  vector& v;
  int i;
public:
  vector_iterator(vector& r) { i=0; v=r; }
  int operator()() {
    return i<v.size() ? v.elem(i++) : 0;
  }
};
```

It can now be used, as in:

```
void f(vector& v) {
  vector_iterator next(v);
  int i;
  while (i=next()) print(i);
}
```

## Iterators (alternative)

The iterator mechanism can be put in the "container" type, if preferred.

```
class vector {
  int* v;
  int i;
  int current;
public:
  int next() { return (++current < sz) ? v[current] : 0; }
  int curr() { return v[current];
  int prev() { return (0 <= --current) ? v[current] : 0; }
};
```

It can now be used, as in:

```
void f(vector& v) {
  vector v(sz);
  int i;
  while (i=v.next()) print(i);
}
```

## Multiple Implementations

```
template<class T> class stack {
public:template<class T> class stack {
  virtual void push(T) = 0; // pure virtual function
  virtual T pop() = 0;
};
```

This declares an abstract class. It can be used, but not created.

```
stack<cat> s; // error: stack is abstract

void some_fn(stack<cat> s, cat kitty) { // ok
  s.push(kitty);
  cat c2 = s.pop();
  ...
}
```

## Multiple Implementations

```
template<class T> class aStack : public stack<T> {
  // actual representation of a stack object
  // in this case an array
  ...
public:
  aStack(int size);
  ~aStack();
  void push(T);
  T pop();
};
```

Elsewhere we can create a list based stack.

```
template<class T> class lStack : public stack<T> { ...
};
```

We can now create stacks of both sorts

```
void g() {
  lStack<cat> s1(100);
  aStack<cat> s2(100);

  cat ginger;
  cat snowball;

  some_fn(s1, ginger);
  some_fn(s2, snowball);
}
```

## Multiple Inheritance

Multiple inheritance is when a class inherits from more than one base class. C++ allows multiple inheritance many languages (eg Java) do not.

```
class my_displayed_task : public displayed, public task {
  // my stuff
};

class my_task : public task { // not displayed
  // my stuff
};

class my_displayed : public displayed { // not a task
  // my stuff
};
```

Using only single inheritance leads to code duplication and loss of flexibility – typically both.

## Ambiguity

Multiple inheritance cause ambiguity when two parents have methods with the same name. Such ambiguity can be solved at compile time.

```
class A { public: void f(); ... }
class B { public: void f(); ... }
class C : public A, public B { ... }

void g(C* p) {
  p->f(); // error: ambiguous
}
```

A solution is the following:

```
class C : public A, public B {
  ...
public:
  void f();
  ...
}

void C::f()
{ // C's own stuff
  A::f();
  B::f();
}
```