FORTRAN

CS4100

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From *Principles of Programming Languages: Design, Evaluation, and Implementation (Third Edition),* by Bruce J. MacLennan, Chapter 2, and based on slides by Istvan Jonyer.

Highlights of Psuedo-Code

- Virtual computer
  - More regularity
  - Higher level
- Decreased chance of errors
  - Automate tedious and error-prone tasks
- Increased security
  - Error checking
- Simplify debugging
  - trace

Now: FORTRAN The First Generation

- Early 1950s
  - Simple assemblers and libraries of subroutines were tools of the day
  - Automatic programming was considered unfeasible
  - Good coders liked being masters of the trade
- Laning and Zierler at MIT in 1952
  - Algebraic language

Backus at IBM

- Visionary at IBM
- Recognized need for faster coding practice
- Need "language" that allows decreasing costs to linear, in size of the program
- Speedcoding for IBM 701
  - Language based on mathematical notation
  - Interpreter to simulate floating point arithmetic

Backus at IBM

- Goals
  - Get floating point operations into hardware: IBM 704
    - Exposes deficiencies in pseudo-code
  - Decrease programming costs
    - Programmers to write in conventional mathematical notation
    - Still generate efficient code
- IBM authorizes project
  - Backus begins outlining FORTRAN
    - IBM Mathematical FORmula TRANslating System
  - Has few assistants
  - Project is overlooked (greeted with indifference and skepticism according to Dijkstra)

Meanwhile

- Grace Hopper organizes Symposia via Office of Naval Research (ONR)
- Backus meets Laning and Zierler
- Later (1978) Backus says:
  - "As far as we were aware we simply made up the language as we went along. We did not regard language design as a difficult problem, merely as a simple prelude to the real problem: designing a compiler which could produce efficient programs."
- FORTRAN compiler works!

FORTRAN timeline

- 1954: Project approved
- 1957: FORTRAN
  - First version released
- 1958: FORTRAN II and III
  - Still many dependencies on IBM 704
- 1962: FORTRAN IV
  - "ANS FORTRAN" by American National Standards Institute
  - Breaks machine dependence
  - Few implementations follow the specifications
- We'll look at 1966 ANS FORTRAN

FORTRAN

- Goals
  - Decrease programming costs (to IBM)
  - Efficiency

Sample FORTRAN program

```
      DIMENSION DTA(900)
      SUM 0.0
      READ 10, N
10    FORMAT(I3)
      DO 20 I = 1, N
      READ 30, DTA(I)
30    FORMAT(F10.6)
      IF (DTA(I)) 25, 20, 20
25    DTA(I) = -DTA(I)
20    CONTINUE
      …
```

Structural Organization

- Preliminary specification did not include subprograms (like in pseudo-code)
- FORTRAN I, however, already included subprograms

Main program
Subprogram 1
.
.
.
Subprogram n

Constructs

- Declarative constructs
  - (First part in pseudo-code: data initialization)
  - Declare facts about the program, to be used at compile-time
- Imperative constructs
  - (Second part in pseudo-code: program)
  - Commands to be executed during run-time

Declarative Constructs

- Declarations include
  - Allocate area of memory of a specified size
  - Attach symbolic name to that area of memory
  - Initialize the memory
- FORTRAN example
  - `DIMENSION DTA (900)`
  - `DATA DTA, SUM / 900*0.0, 0.0`
    - initializes DTA to 900 zeroes
    - SUM to 0.0

Imperative Constructs

- Categories:
  - Computational
    - E.g.: Assignment, Arithmetic operations
    - FORTRAN: `AVG = SUM / FLOAT(N)`
  - Control-flow
    - E.g.: comparisons, loop
    - FORTRAN:
      - `IF`-statements
      - `DO` loop
      - `GOTO`
  - Input/output
    - E.g.: read, print
    - FORTRAN: Elaborate array of I/O instructions (tapes, drums, etc.)

Building a FORTRAN Program

- Interpretation unacceptable, since the selling point is speed
- Need the following stages to build:
  1. Compilation
     Translate code to relocatable object code
  2. Linking
     Incorporating libraries (resolving external dependencies)
  3. Loading
     Program loaded into memory; converted from relocatable to absolute format
  4. Execution
     Control is turned over to the processor

Compilation

- Compilation has 3 phases
  - Syntactic analysis
    - Classify statements, constructs and extract their parts
  - Optimization
    - FORTRAN has considerable optimizations, since that was the selling point
  - Code synthesis
    - Put together parts of object code instructions in relocatable format

DESIGN: Control Structures

- Control structures control flow in the program
- Most important statement in FORTRAN:
  - Assignment Statement

DESIGN: Control Structures

- Machine Dependence (1st generation)
- In FORTRAN, these were based on native IBM 704 branch instructions
  - "Assembly language for IBM 704"

FORTRAN II statement	IBM 704 branch operation
`GOTO n`	`TRA k (transfer direct)`
`GOTO n, (n1, n2,…,nm)`	`TRA i (transfer indirect)`
`GOTO (n1, n2,…,nm), n`	`TRA i,k (transfer indexed)`
`IF (a) n1, n2, n3`	`CAS k`
`IF ACCUMULATOR OVERFLOW n1, n2`	`TOV k`
…	…

Arithmetic IF-statement

- Example of machine dependence
  - `IF (a) n1, n2, n3`
  - Evaluate a: branch to
    - n1: if -,
    - n2: if 0,
    - n3: if +
  - CAS instruction in IBM 704
- More conventional IF-statement was later introduced
  - `IF (X .EQ. A(I)) K = I - 1`

Principles of Programming

- The Portability Principle
  - Avoid features or facilities that are dependent on a particular computer or a small class of computers.

GOTO

- Workhorse of control flow in FORTRAN
- 2-way branch:

```
    IF (condition) GOTO 100
          case for false
    GOTO 200
100       case for true
200
```

- Equivalent to *if-then-else* in newer languages

Reversing TRUE and FALSE

- To get *if-then-else* –style if:

```
    IF (.NOT. (condition)) GOTO 100
          case for true
    GOTO 200
100       case for false
200
```

n-way Branching with Computed GOTO

```
    GOTO (L1, L2, L3, L4 ), I
10 case 1
     GOTO 100
20 case 2
     GOTO 100
30 case 3
     GOTO 100
40 case 4
     GOTO 100
100
```

- Transfer control to label L_k if I contains k
- Jump Table

n-way Branching with Computed GOTO

```
    GOTO (10, 20, 30, 40 ), I
10 case 1
     GOTO 100
20 case 2
     GOTO 100
30 case 3
     GOTO 100
40 case 4
     GOTO 100
100
```

- IF and GOTO are *selection statements*

Loops

- Loops are implemented using combinations of IF and GOTOs
- Trailing-decision loop:

```
100 ...body of loop...
      IF (loop not done) GOTO 100
```

- Leading-decision loop:

```
100 IF (loop done) GOTO 200
      ...body of loop...
     GOTO 100
200 ...
```

- Readable?

But wait, there's more!

- Mid-decision loop:

```
100 …first half of loop…
     IF (loop done) GOTO 200
     …second half of loop…
    GOTO 100
200 …
```

Hmmm…

- Very difficult to know what control structure is intended
- Spaghetti code
- Very powerful
- Must be a principle in here somewhere

Principles of Programming

- The Structure Principle (Dijkstra)
  - The static structure of the program should correspond in a simple way to the dynamic structure of the corresponding computations.
- What does this mean?
  - Should be able to visualize behavior of program based on written form

GOTO: A Two-Edged Sword

- Very powerful
  - Can be used for good or for evil
- But seriously is GOTO good or bad?
  - Good: very flexible, can implement elaborate control structures
  - Bad: hard to know what is intended
  - Violates the structure principle

But that's not all!

- We just saw the Computed GOTO:
  `GOTO (L1, L2, …, Ln), I` ($L_1, L_2, \ldots, L_n$)
  - Jumps to label 1, 2, …
- Now consider the Assigned GOTO:
  `GOTO N, (L1, L2, …, Ln)` ($L_1, L_2, \ldots, L_n$)
  - Jumps to ADDRESS in N
  - List of labels not necessary
  - Must be used with ASSIGN-statement
    `ASSIGN 20 TO N`
  - Put address of statement 20 into N
  - Not the same as N = 20 !!!!

Ex: Computed and Assigned GOTOs

```
ASSIGN 20 TO N
```

- N has address of stmt 20, say it is 347

```
GOTO (20, 30, 40, 50), N
```

- Look for 347 in jump table - out of range
- Not checked
- Fetch value at 347 and use as destination for jump
- Problem???
  - Computed should have been Assigned

Ex: Computed and Assigned GOTOs

```
I = 3
```

- I expected to have an address

```
GOTO I, (20, 30, 40, 50)
```

- GOTO statement with address 3
  - Probably in area used by system, i.e. not a stmt
- Problem???
  - Assigned should have been computed

Principles of Programming

- The Syntactic Consistency Principle
  - Things that look similar should be similar and things that look different should be different.

Syntactic Consistency

- Best to avoid syntactic forms that can be converted to other forms by a simple error
  - ** and *
  - Weak Typing (more on this later)
    - Integer variables
      - Integers
      - Addresses of statements
      - Character strings
    - Maybe a LABEL type?
      - Catch errors at compile time

Even worse…

- Confusing the two GOTOs will not be caught by the compiler
- Violates the defense in depth principle

Principles of Programming

- The Defense in Depth Principle
  - If an error gets through one line of defense, then it should be caught by the next line of defense.

The DO-loop

- Fortunately, FORTRAN provides the DO-loop
- Higher-level than IF-GOTO-style control structures
  - No direct machine-equivalency

```
      DO 100 I = 1, N
      A(I) = A(I) * 2
100 CONTINUE
```

- I is called the *controlled variable*
- CONTINUE must have matching label
- DO allows stating what we *want*: higher level
  - Only built-in higher level structure

Nesting

- The DO-loop can be nested

```
DO 100 I = 1, N
    ...
    DO 200 J = 1, N
        ...
    200 CONTINUE
100 CONTINUE
```

  - They must be correctly nested
  - Optimized: controlled variable can be stored in index register
  - Note: we could have done this with GOTO

Principles of Programming

- Preservation of Information Principle
  - The language should allow the representation of information that the user might know and that the compiler might need.
- Do-loop makes explicit
  - Control variable
  - Initial and final values
  - Extent of loop
- If and GOTO
  - Compiler has to figure out

Subprograms

- AKA subroutine
  - User defined
  - Function returns a value
    - Can be used in an expression
- Important, late addition
- Why are they important?
  - Subprograms define procedural abstractions
  - Repeated code can be abstracted out, variables formalized
  - Allow large programs to be modularized
    - Humans can only remember a few things at a time (about 7)

Subprograms

```
SUBROUTINE Name(formals)
...body...
RETURN
END

…
CALL Name (actuals)
```

- When invoked
  - Using call stmt
  - Formals bound to actuals
  - Formals aka dummy variables

Example

```
SUBROUTINE DIST (d, x, y)
D = X – Y
IF (D .LT. 0) D = -D
RETURN
END

…
CALL DIST (DIFFER, POSX, POSY)
…
```

Principles of Programming

- The Abstraction Principle
  - Avoid requiring something to be stated more than once; factor out the recurring pattern.

Libraries

- Subprograms encourage libraries
  - Subprograms are independent of each other
  - Can be compiled separately
  - Can be reused later
  - Maintain library of already debugged and compiled useful subprograms

Parameter Passing

- Once we decide on subprograms, we need to figure out how to pass parameters
- Fortran parameters
  - Input
  - Output
    - Need address to write to
  - Both

Parameter Passing

- Pass by reference
  - On chance may need to write to
    - all vars passed by reference
  - Pass the address of the variable, not its value
  - Advantage:
    - Faster for larger (aggregate) data constructs
    - Allows output parameters
  - Disadvantage:
    - Address has to be de-referenced
      - Not by programmer—still, an additional operation
    - Values can be modified by subprogram
    - Need to pass size for data constructs - if wrong?

A Dangerous Side-Effect

- What if parameter passed in is not a variable?

```
SUBROUTINE SWITCH (N)
N = 3
RETURN
END
…
CALL SWITCH (2)
```

- The literal 2 can be changed to the literal 3 in FORTRAN's literal table!!!
  - I = 2 + 2   I = 6????
  - Violates security principle

Principles of Programming

- Security principle
  - No program that violates the definition of the language, or its own intended structure, should escape detection.

Pass by Value-Result

- Also called *copy-restore*
- Instead of pass by reference, copy the value of actual parameters into formal parameters
- Upon return, copy new values back to actuals
- Both operations done by caller
  - Can know not to copy meaningless result
    - E.g. actual was a constant or expression
- Callee never has access to caller's variables

Activation Records

- What happens when a subprogram is called?
  - Transmit parameters
  - Save caller's status
  - Enter the subprogram
  - Restore caller's state
  - Return to caller

What happens exactly?

- Before subprogram invocation:
  - Place parameters into callee's activation record
  - Save caller's status
    - Save content of registers
    - Save instruction pointer (IP)
  - Save pointer to caller's activation record in callee's activation record
  - Enter the subprogram

What happens exactly?

- Returning from subprogram:
  - Restore instruction pointer to caller's
  - Return to caller
  - Caller needs to restore its state (registers)
  - If subprogram is a function, return value must be made accessible

Contents of Activation Record

- Parameters passed to subprogram
- P (resumption address)
- Dynamic link (address of caller's activation record)
- Temporary areas for storing registers

DESIGN: Data Structures

- First data structures
  - Suggested by mathematics
    - Primitives
    - Arrays

Primitives

- Primitives are scalars only
  - Integers
  - Floating point numbers
  - Double-precision floating point
  - Complex numbers
  - No text (string) processing

Representations

- Word-oriented
  - Most commonly 32 bits
- Integer
  - Represented on 31 bits + 1 sign bit
- Floating point
  - Using scientific notation: characteristic + mantissa

sm	sc	c_7	…	c_0	m_{21}	…	m_0

Arithmetic Operators

- 2 + 3.1 = ?
  - 2 is integer, 3.1 is floating point
- How do we handle this situation?
  - Explicit type-casting: FLOAT(2) + 3.1
    - Type-casting is also called "*coercion*"
  - FORTRAN: Operators are overloaded
  - Automatic type coercion
    - Always coerce to encompassing set
      - Integer + Float → float addition
      - Float * Double → double multiplication
      - Integer – Complex → complex subtraction
    - Types *dominate* their subsets

Example

- X**(1/3) = ?

  1/3 = 0

  1/3.0 = 0.33333

Hollerith Constants

- Early form of character string in FORTRAN
  - 6HCARMEL is a six character string 'CARMEL' (H is for Hollerith)
  - Second-class citizens
    - No operations allowed
    - Can be read into an integer variable, which cannot (should not) be altered
- Problems
  - Integer representing a Hollerith constant may be altered, which makes no sense
- Weak typing
  - No type checking is performed

Constructor: Array

- Constructor
  - Method to build complex data structures from primitive ones
- FORTRAN only has array constructors

```
DIMENSION DTA, COORD(10,10)
```

  - Initialization is not required
  - Maximum 3 dimensions

Representation

- Simple, intuitive representation
- Column-major order
  - Most languages do row-major order
  - Addressing equation:
    - $\alpha\{A(2)\} = \alpha\{A(1)\} + 1 = \alpha\{A(1)\} - 1 + 2$
    - $\alpha\{A(i)\} = \alpha\{A(1)\} - 1 + i$
    - $\alpha\{A(i,j)\} = \alpha\{A(1,1)\} + (j - 1)m + i - 1$
    - FORTRAN uses 1-based addressing
      - One addressable slot of each elt

Element	Address
A(1,1)	A
A(2,1)	A + 1
…	
A(m,1)	A + m - 1
A(1,2)	A + m
…	
A(m,2)	A + 2m - 1
…	
A(m,n)	A + nm - 1

Optimizations

- Arrays are mostly associated with loops
  - Most programmers initialize controlled variable to 1, and reference array A(i)
  - Optimization:
    - Initialize controlled variable to address of array element
    - Therefore, we'll increment address itself
    - Dereference controlled variable to get array element

Subscripts

- Subscripts can be expressions
  - A(i+m*c)
  - This defeats above optimization
  - Therefore, subscripts are limited to
    - c and c' are integers, v is an integer variable
    - c
    - v
    - v+c, v-c
    - c*v
    - c*v+c', c*v-c'
  - A(J - 1) ok; A(1+J) not ok
- Optimizations like this sold FORTRAN

DESIGN: Name Structures

- What do name structures structure?
  - Names, of course!
- Primitives bind names to objects
  - INTEGER I, J, K
    - Allocate integers I, J, and K, and bind the names to memory locations
    - Declare: name, type, storage

Declarations

- Declarations are non-executable statements
- Unlike IF, GOTO, etc., which are executable statements
- Static allocation
  - Allocated once, cannot be deallocated for reuse
  - FORTRAN does not do dynamic allocation

Optional Declaration

- FORTRAN does not require variables to be declared
  - First use will declare a variable
- What's wrong with this?
  - COUNT = COUMT + 1
  - What if first use is not assignment?
- Convention:
  - Variables starting with letters i, j, k, l, m, n are integers
  - Others are floating point
  - Bad practice: Encourages funny names (KOUNT, ISUM, XLENGTH…)

Now: Semantics (meaning)

- "They went to the bank of the Rio Grande."
- What does this mean?
- How do we know?
- CONTEXT, CONTEXT, CONTEXT

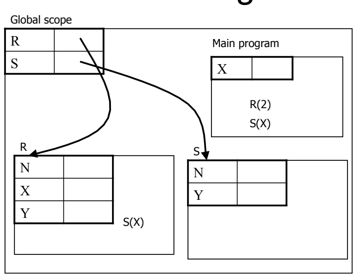
Programming Languages

- X = COUNT(I)
- What does this mean
  - X integer or real
  - COUNT array or function
- Again Context
  - Set of variables visible when statement is seen
- Context is called ENVIRONMENT

SCOPE

- Scope of a binding of a name
  - Region of program where binding is visible
- In FORTRAN
  - Subprogram names GLOBAL
    - Can be called from anywhere
  - Variable names LOCAL
    - To subprogram where declared

Contour Diagram



Once we have subprograms…

- We need to find a way to share data
  - Parameters
    - Pass by reference
    - Pass by value-result
      - Caller copies value of actual to formal variable
      - On return, caller copies result value to actual
        - » Omit for constants or expressions as actuals

Once we have subprograms…

- Share Data With Just Parameters?
  - Cumbersome, and hard to maintain
  - Produces long list of parameters
  - If data structure changes, there are many changes to be made
  - Violates information hiding

Sharing Data

- FORTRAN's solution:
- COMMON blocks allow more flexibility
  - Allows sharing data between subprograms
  - Scope rules necessitate this
- Consider a symbol table

```
SUBROUTINE ARRAY2 (N, L, C, D1, D2)
COMMON /SYMTAB/ NAMES(100), LOC(100), TYPE(100)
...
SUBROUTINE VAR (N, L, C)
COMMON /SYMTAB/ NAMES(100), LOC(100), TYPE(100)
```

COMMON Problems

- Tedious to write
- Unreadable
- Virtually impossible to change AND
- COMMON permits aliasing, which is dangerous
  - If COMMON specifications don't agree, misuse is possible

Aliasing

- The ability to have more than one name for the same memory location
- Very flexible!

```
COMMON /B/ M, A(100)

COMMON /B/ X, K, C(50), D(50)
```

EQUIVALENCE

- Since dynamic memory allocation is not supported, and memory is scarce, FORTRAN has EQUIVALENCE

```
DIMENSION INDATA(10000), RESULT(8000)
EQUIVALENCE INDATA(1), RESULT(8)
```

- Allows a way to explicitly alias two arrays to the same memory

EQUIVALENCE

- This is only to be used when usage of INDATA and RESULT do not overlap
- Allows access to different data types (float as if it was integer, etc.)
- Has same dangers as COMMON

DESIGN: Syntactic Structures

- Languages are defined by lexics and syntax
  - Lexics
    - Way to combine characters to form words or symbols
    - E.g. Identifier must begin with a letter, followed by no more than 5 letters or digits
  - Syntax
    - Way to combine symbols into meaningful instructions
- Syntactic analysis:
  - Lexical analyzer (scanner)
  - Syntactic analyzer (parser)

Fixed Format Lexics

- Still using punch-cards!
- Particular columns had particular meanings
- Statements (columns 7-72) were free format

Columns	Purpose
1-5	Statement number
6	Continuation
7-72	Statement
73-90	Sequence number

Blanks Ignored

- FORTRAN ignored spaces (not just white spaces)
- Thisisveryunfortunate!

```
DIMENSION INDATA(10000), RESULT(8000)
D I M E N S I O N I N D A T A (1 0 0 0 0), R E S U L T (8000)
DIMENSIONINDATA(10000),RESULT(8000)
```

- Lexing and parsing such a language is very difficult

Blanks Ignored

- In combination with other features, it promoted mistakes

```
DO 20 I = 1. 100
DO 20 I = 1, 100
DO20I = 1.100
```

- Variable DO20I is unlikely, but . and , are next to each other on the keyboard…

No Reserved Words

- FORTRAN allows variable named IF

```
DIMENSION IF(100)
```

- How do you read this?

```
IF (I - 1) = 1 2 3
IF (I - 1) 1, 2, 3
```

- The compiler does not know what `IF (I - 1)` will be
  - Needs to see , or = to decide

Algebraic Notation

- One of the main goals was to facilitate scientific computing
  - Algebraic notation had to look like math
  - (-B + SQRT(B**2 – 4*AA*C))/(2*A)
  - Very good, compared to our pseudo-code
- Problems
  - How do you parse and execute such a statement?

Operators Need Precedence

- $b^2 – 4ac == (b^2) – (4ac)$
- $ab^2 == a(b^2)$
- Precedence rules
  1. Exponentiation
  2. Multiplication and division
  3. Addition and subtraction
- Operations on the same level are associated to the left (read left to right)
- How about unary operators (-)?

Some Highlights

- Integer type is overworked
  - Integer
  - Character strings
  - Addresses
- Weak typing
- Combine the two and we have a security loophole
  - Meaningless operations can be performed without warning

Some Highlights

- Arrays
  - Only data structure
  - Data constructor
  - Static
  - Limited to three dimensions
  - Restrictions on index expressions
  - Optimized
  - Column major order for 2-dimensional
  - Not required to be initialized