Early History of Compiling

Uday Khedker

(www.cse.iitb.ac.in/~uday)

Department of Computer Science and Engineering,

Indian Institute of Technology, Bombay

January 2023

Outline

- What is a Compiler
- The Birth of a compiler
- Modern challenges
- Conclusions

What is a Compiler?

Uday Khedker
IIT Bombay

Implementation Mechanisms

Source Program

↓

Translator

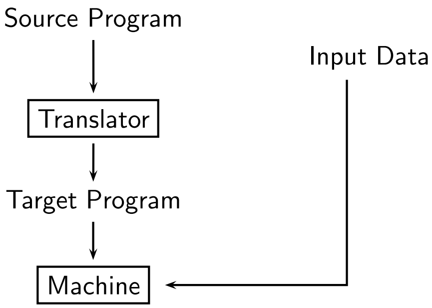
↓

Target Program

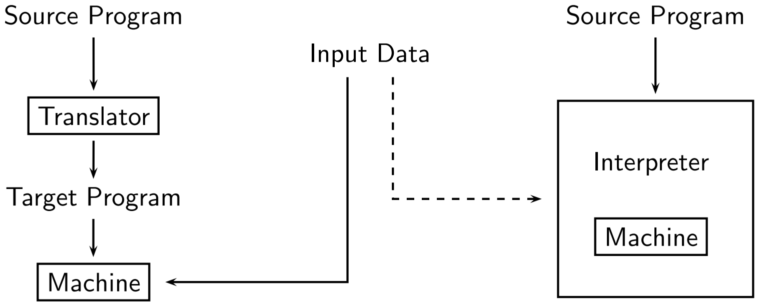
↓

Machine

Implementation Mechanisms



Implementation Mechanisms



Implementation Mechanisms as "Bridges"

- "Gap" between the "levels" of program specification and execution

Program Specification

Machine

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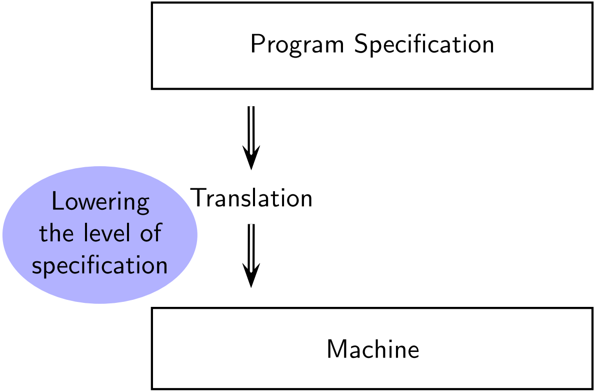

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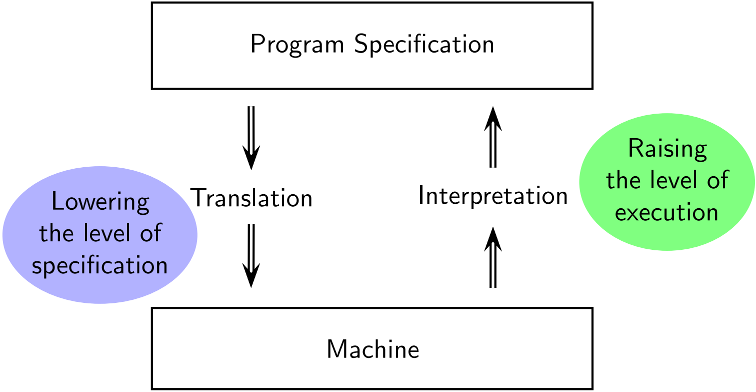

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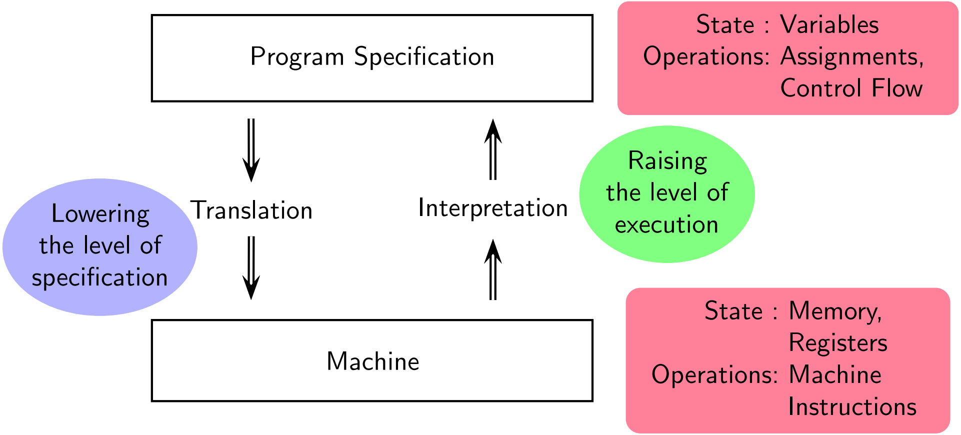

A Source Program in C++: High Level Abstraction

```
#include <iostream>
using namespace std;

int main()
{
    int n, fact=1;

    cout << "Enter the number: ";
    cin >> n;
    for (int i=n; i > 0; i--)
        fact = fact * i;

    cout << "The factorial of " << n << " is " << fact << endl;

    return 0;
}
```

Its Target Program: Low Level Abstraction (1)


```
f3 0f 1e fa 48 83 ec 08 48 8b 05 d9 2f 00 00 48 85 c0 74 02 ff d0 48 83 c4
08 c3 ff 35 5a 2f 00 00 f2 ff 25 5b 2f 00 00 0f 1f 00 f3 0f 1e fa 68 00 00
00 00 f2 e9 e1 ff ff ff 90 f3 0f 1e fa 68 01 00 00 00 f2 e9 d1 ff ff ff 90
f3 0f 1e fa 68 02 00 00 00 f2 e9 c1 ff ff ff 90 f3 0f 1e fa 68 03 00 00 00
f2 e9 b1 ff ff ff 90 f3 0f 1e fa 68 04 00 00 00 f2 e9 a1 ff ff ff 90 f3 0f
1e fa 68 05 00 00 00 f2 e9 91 ff ff ff 90 f3 0f 1e fa 68 06 00 00 00 f2 e9
81 ff ff ff 90 f3 0f 1e fa f2 ff 25 1d 2f 00 00 0f 1f 44 00 00 f3 0f 1e fa
f2 ff 25 d5 2e 00 00 0f 1f 44 00 00 f3 0f 1e fa f2 ff 25 cd 2e 00 00 0f 1f
44 00 00 f3 0f 1e fa f2 ff 25 c5 2e 00 00 0f 1f 44 00 00 f3 0f 1e fa f2 ff
25 bd 2e 00 00 0f 1f 44 00 00 f3 0f 1e fa f2 ff 25 b5 2e 00 00 0f 1f 44 00
00 f3 0f 1e fa f2 ff 25 ad 2e 00 00 0f 1f 44 00 00 f3 0f 1e fa f2 ff 25 a5
2e 00 00 0f 1f 44 00 00 f3 0f 1e fa 31 ed 49 89 d1 5e 48 89 e2 48 83 e4 f0
50 54 4c 8d 05 86 02 00 00 48 8d 0d 0f 02 00 00 48 8d 3d c1 00 00 00 ff 15
92 2e 00 00 f4 90 48 8d 3d b9 2e 00 00 48 8d 05 b2 2e 00 00 48 39 f8 74 15
48 8b 05 6e 2e 00 00 48 85 c0 74 09 ff e0 0f 1f 80 00 00 00 00 c3 0f 1f 80
00 00 00 00 48 8d 3d 89 2e 00 00 48 8d 35 82 2e 00 00 48 29 fe 48 89 f0 48
c1 ee 3f 48 c1 f8 03 48 01 c6 48 d1 fe 74 14 48 8b 05 45 2e 00 00 48 85 c0
74 08 ff e0 66 0f 1f 44 00 00 c3 0f 1f 80 00 00 00 00 f3 0f 1e fa 80 3d ad
30 00 00 00 75 2b 55 48 83 3d f2 2d 00 00 00 48 89 e5 74 0c 48 8b 3d 26 2e
00 00 e8 b9 fe ff ff e8 64 ff ff ff c6 05 85 30 00 00 01 5d c3 0f 1f 00 c3
```

Its Target Program: Low Level Abstraction (2)

```
0f 1f 80 00 00 ff ff e8 64 ff ff ff c6 05 85 30 00 00 01 5d c3 0f 1f 00 c3
0f 1f 80 00 00 00 00 f3 0f 1e fa e9 77 ff ff ff f3 0f 1e fa 55 48 89 e5 48
83 ec 20 64 48 8b 04 25 28 00 00 00 48 89 45 f8 31 c0 c7 45 f0 01 00 00 00
48 8d 35 d3 0d 00 00 48 8d 3d 07 2e 00 00 e8 92 fe ff ff 48 8d 45 ec 48 89
c6 48 8d 3d 14 2f 00 00 e8 5f fe ff ff 8b 45 ec 89 45 f4 83 7d f4 00 7e 10
8b 45 f0 0f af 45 f4 89 45 f0 83 6d f4 01 eb ea 48 8d 35 a4 0d 00 00 48 8d
3d c5 2d 00 00 e8 50 fe ff ff 48 89 c2 8b 45 ec 89 c6 48 89 d7 e8 80 fe ff
ff 48 8d 35 93 0d 00 00 48 89 c7 e8 31 fe ff ff 48 89 c2 8b 45 f0 89 c6 48
89 d7 e8 61 fe ff ff 48 89 c2 48 8b 05 17 2d 00 00 48 89 c6 48 89 d7 e8 1c
fe ff ff b8 00 00 00 00 48 8b 4d f8 64 48 33 0c 25 28 00 00 00 74 05 e8 13
fe ff ff c9 c3 f3 0f 1e fa 55 48 89 e5 48 83 ec 10 89 7d fc 89 75 f8 83 7d
fc 01 75 32 81 7d f8 ff ff 00 00 75 29 48 8d 3d 72 2f 00 00 e8 f4 fd ff ff
48 8d 15 f5 2c 00 00 48 8d 35 5f 2f 00 00 48 8b 05 d7 2c 00 00 48 89 c7 e8
97 fd ff ff 90 c9 c3 f3 0f 1e fa 55 48 89 e5 be ff ff 00 00 bf 01 00 00 00
e8 9c ff ff ff 5d c3 66 2e 0f 1f 84 00 00 00 00 00 90 f3 0f 1e fa 41 57 4c
8d 3d 03 2a 00 00 41 56 49 89 d6 41 55 49 89 f5 41 54 41 89 fc 55 48 8d 2d
fc 29 00 00 53 4c 29 fd 48 83 ec 08 e8 7f fc ff ff 48 c1 fd 03 74 1f 31 db
0f 1f 80 00 00 00 00 4c 89 f2 4c 89 ee 44 89 e7 41 ff 14 df 48 83 c3 01 48
39 dd 75 ea 48 83 c4 08 5b 5d 41 5c 41 5d 41 5e 41 5f c3 66 66 2e 0f 1f 84
00 00 00 00 00 f3 0f 1e fa c3 f3 0f 1e fa 48 83 ec 08 48 83 c4 08 c3
```

Commands to Obtain the Low Level Abstraction

- Write the program and name the file `fact-iterative.cc`
- `g++ fact-iterative.cc` produces the executable in `a.out` file
- `strip a.out` removes names from the executable `a.out`
- `file a.out` produces the following output

  ```
  a.out: ELF 64-bit LSB shared object, x86-64, version 1
  (SYSV), dynamically linked, interpreter
  /lib64/ld-linux-x86-64.so.2,
  BuildID[sha1]=0c218bf025a20bc43339dfd15cec41adc1c13946, for
  GNU/Linux 3.2.0, stripped
  ```

- `objdump -d a.out` produces the hexadecimal form along with assembly program

Why Is Compiler Construction a Relevant Subject?

Very few people write compilers any way

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Very few people write compilers any way

- Translation and interpretation are fundamental to CS at a conceptual level
- Computer Science is all about building layers of abstractions and bridging the gaps between successive layers
- Knowing compilers internals makes a person a much better programmer

  Writing programs whose data is programs

The Birth of a Compiler

The First Compiler and “Real” Programming Language

- Fortran (later FORTRAN): 1956, Compiler: 1957
- Machine: IBM 704
- Creator: John Backus

  Richard Goldberg, Sheldon F. Best, Harlan Herrick, Peter Sheridan, Roy Nutt, Robert Nelson, Irving Ziller, Harold Stern, Lois Haibt, and David Sayre

The Beauty and The Beast

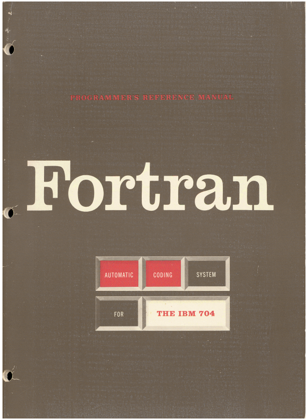

Image Source: Wikipedia

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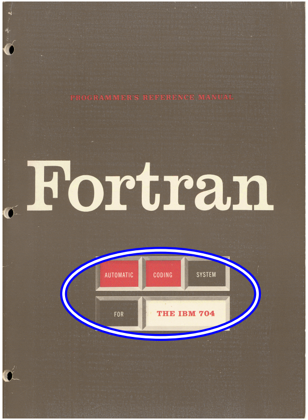

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Pioneers of Programming Languages (Knuth-Pardo, 1976)

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- Many efforts, and yet a breakthrough had to wait for Backus and his team
- We need to go back into the history to understand why it was so

Computing: Hand to Hand Combat with Machine (1)

- Computing was a black art
- Things available:

  The problem, the machine, the manual, and individual creativity
- *"Computers were pretty crazy things. They had very primitive instructions and extremely bizarre input-output facilities."*
- Example: Selective Sequence Electronic Calculator (SSEC), 1948 - 1952

  Store of 150 words, Vacuum tubes and electro-mechanical relays

Computing: Hand to Hand Combat with Machine (2)

- No tools, only memory maps :
  - Machine Program in 0's and 1's + Data
  - Actual feeding by flipping switches

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  - transfer control to the program
- *Macro-processor/Macro-assembler*
  - Combining many instructions for repeated use

Computing: Hand to Hand Combat with Machine (3)

- The story of paper tape
  - Punched paper tape glued to form a paper loop
  - Problem would appear and then disappear
  - Pattern repeated many times
  - Mobius strip

(Image source: Wikipedia)

- Debugging by the ear. When IBM 701 Defence Calculator arrived
  "How are we going to debug this enormous silent monster"

Beliefs of the Times

- Popular Mechanics Prediction in 1949
  Computers in the future may weigh no more than 1.5 tons

  (ENIAC, completed in 1947 weighed almost 30 tons)

- Editor of Prentice Hall business books, 1957
  I have travelled the length and breadth of this country and talked with the best people, and I can assure you that data processing is a fad that won't last out the year

Octal Humour

- *"Why can't programmers tell the difference between Christmas and New Year's Eve? Because 25 in decimal is 31 in octal."*
- *"We programmed it in octal. Thinking I was still a mathematician, I taught myself to add, subtract, and multiply, and even divide in octal. I was really good, until the end of the month, and then my check book didn't balance! It stayed out of balance for three months until I got hold of my brother who was a banker. After several evenings of work he informed me that at intervals I had subtracted in octal. And I faced the major problem of living in two different worlds."*

  "That may have been one of the things that sent me to get rid of octal as far as possible."

— Grace Hopper

The Priesthood of Computing

- *"Programming in the America of the 1950s had a vital frontier enthusiasm virtually untainted by either the scholarship or the stuffiness of academia."*
- *"Programmer inventors of the early 1950s were too impatient to hoard an idea until it could be fully developed and a paper written. They wanted to convince others. Action, progress, and outdoing one's rivals were more important than mere authorship of a paper."*
- *"An idea was the property of anyone who could use it and the scholarly practice of noting references to sources and related work was almost universally unknown or unpractised."*

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Obstacles in Creation of a High Level Language

- Priesthood wanted to preserve the order

  "Priesthood wanted and got simple mechanical aids for the clerical drudgery which burdened them, but they regarded with hostility and derision more ambitious plans to make programming accessible to a larger population. To them, it was obviously a foolish and arrogant dream to imagine that any mechanical process could possibly perform the mysterious feats of invention required to write an efficient program."

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- There also were purveyors of snake oil

  "The energetic public relations efforts of some visionaries spread the word that their "automatic programming" systems had almost human abilities to understand the language and needs of the user; whereas closer inspection of these same systems would often reveal a complex, exception-ridden performer of clerical tasks which was both difficult to use and inefficient."

The A2 Compiler

- Adding instructions to the machine viz. floating point operations
  - Programmers had a library of subroutine
  - They needed to copy the subroutine on the coding sheets by hand and change addresses manually
- Grace Hopper added a "call" operation whereby
  - the machine would copy the code
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The name "Compiler" was used because it put together a set of subroutines

The "Real" High Level Languages

- Conrad Zuse's Plankalkul developed in a small village in Germany (1945)
  - "Program Calculus"
  - Only design, no implementation
    (Computers were destroyed in world war II)
- Laning and Zierler's language for the WHIRLWIND at MIT (1953)
  - Fully algebraic in terms of supporting expressions
  - Very inefficient

Challenges for Creation of High Level Languages

- The tyranny of OR

  Expressiveness OR Efficiency

- Expressiveness:

  Higher level abstraction, features not supported by hardware

- Most time was spent in floating point subroutines
  - Not much attention was paid to address calculation, good use of registers

Challenges for Creation of High Level Languages

- The tyranny of OR
  Expressiveness OR Efficiency
- Expressiveness:
  Higher level abstraction, features not supported by hardware
- Most time was spent in floating point subroutines
  - Not much attention was paid to address calculation, good use of registers
- IBM 704 directly supported fast floating point operations
  - The need of expressiveness vanished revealing inefficiencies
    Clumsy treatment of loops, indexing, references to registers
  - Led to rejection of "automatic programming"

The Genius of John Backus

He made the following important observations

- The main reason of inefficiency was a clumsy treatment of loops and array address computations

  If that could be handled, things may be far different

- The possibility made a lot of economic sense
- Language implementation was far more critical than language design

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  The "TRAN" in "FORTRAN" conveys the spirit

The Genesis of FORTRAN

- Motivation:

  Programming and debugging costs already exceeded the cost of running a program, and as computers became faster and cheaper this imbalance would become more and more intolerable

- Goals: Can a machine translate
  - a sufficiently rich mathematical language into
  - a sufficiently economical program at
  - a sufficiently low cost

  to make the whole affair feasible?

  The generated programs needed to be comparable to hand coded programs in efficiency

The Design Philosophy

- About Language Design
  - *"We simply made up the language as we went along. We did not regard language design as a difficult problem, merely a simple prelude to the real problem: designing a compiler that could produce efficient programs."*
  - *"We had notions of assignment statements, subscripted variables, and the DO statement as the main features. Whatever else was needed emerged as we tried to build a way of programming on these basic ideas."*

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  - Generalize the observations by removing specificities and exceptions

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Effectively, they raised the level of computing from

number processing to processing text that processed numbers

The FORTRAN Project

- Approved in Jan 1954, system delivered in April 1957
- Supportive management
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  - Great team spirit and synergy

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  - Helped in ignoring the doubters and overcome discouragement and despair

FORTRAN Claims (1)

- *"The amount of knowledge necessary to utilize the 704 effectively by means of FORTRAN is far less than the knowledge required to make effective use of the 704 by direct coding.*

  It will be possible to make the full capabilities of the 704 available to a much wider range of people than would otherwise be possible without expensive and time-consuming training programs."

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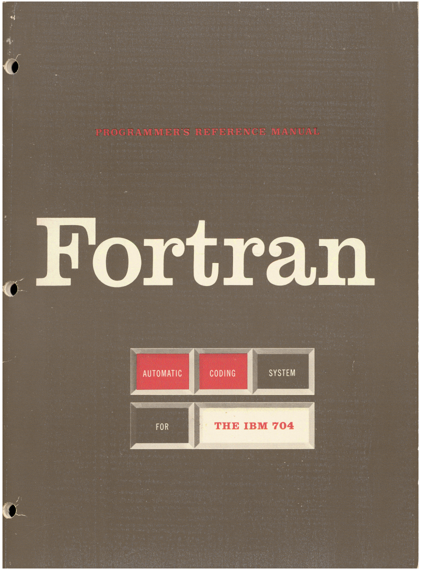
- *"FORT... g a problem which the human coder would have neither the time nor inclination to derive or apply."*

- Replace IBM 704 by your favorite multi-core processor
- Replace "complex lengthy technique" by scheduling for parallel computing
- Imagine a language for it

FORTRAN Claims (2)

"FORTRAN will virtually eliminate coding and debugging"

☺



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Talk Title:
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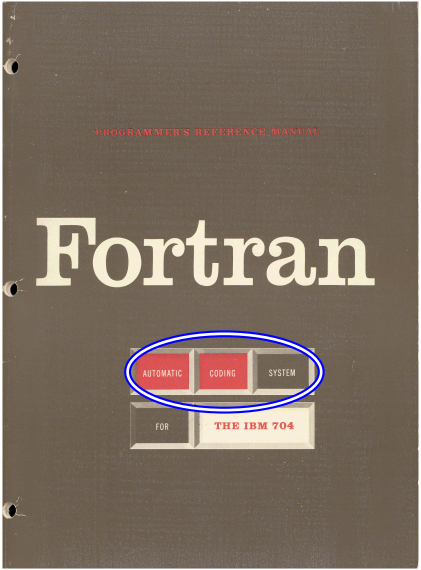

Limitations of FORTRAN I Language

- No reserved words
- Tokenization ignored spaces
- Simplistic functions
- No subprograms, no recursion
- No spaces
- DO loops with limited nesting depth of 3
- Implicit types based on the first letter
- No declarations required

Minor Errors Could be Rather Expensive

- The first American Venus probe was lost because of a computer problem
- A programmer replaced a comma by a dot

Should have been	Was
`DO 10 I = 1, 3`	`DO 10 I = 1.  3`

- What was essentially a DO loop header got treated as an assignment statement `DO10I = 1.3` by the compiler

Fun with FORTRAN

- Implicit types based on the first letter
  - I,J,K,L,M,N: Integer
  - Others: Real

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Fun with FORTRAN

- Implicit types based on the first letter
    - I,J,K,L,M,N: Integer
    - Others: Real

"GOD is real unless declared integer".

- No reserved words

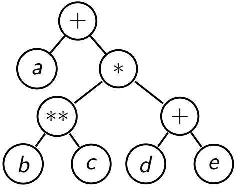
IF (IF .LT. THEN) THEN ELSE = THEN ELSE THEN = ELSE

Contributions of FORTRAN I Compiler

- Phase-wise division of work
- Optimizations:
  - Common subexpressions elimination,
  - Array address optimization in loops
    (a form of strength reduction and induction variable elimination)
  - Register allocation using hierarchical regions
    (optimal under number of loads for straight line code)
- Basic blocks and execution frequency analysis
- Distinction between pseudo registers and hard registers

Expressions in the Programs

- Other "algebraic" compilers needed parenthesis for expressions
- No concept for parsing using grammars

Expression	Expression Tree	Required Syntax
$a + b * *c * (d + e)$		$(a) + ((b * *c) * (d + e))$

FORTRAN Rules for Expressions

1. Any fixed point (floating point) constant, variable, or subscripted variable is an expression of the same mode. Thus 3 and I are fixed point expressions, and $ALPHA$ and $A(I, J, K)$ are floating point expressions.
2. If $SOMEF$ is some function of n variables, and if $E, F, \ldots, H$ are a set of n expressions of the correct modes for $SOMEF$, then $SOMEF(E, F, \ldots, H)$ is an expression of the same mode as $SOMEF$.
3. If E is an expression, and if its first character is not "$+$" or "$-$", then $+E$ and $-E$ are expressions of the same mode as E. Thus $-A$ is an expression, but $--A$ is not.
4. If E is an expression, then (E) is an expression of the same mode as E. Thus $(A), ((A)), (((A)))$, etc. are expressions.
5. If E and F are expressions of the same mode, and if the first character of F is not $+$ or $-$, then $E + F$, $E - F$, $E * F$, E/F are expressions of the same mode.

FORTRAN Expression Handling

- Conventional precedences were used and parenthesis were not required.
- Simple rule of reconstructing parenthesized expressions:

  Assuming three levels of precedences of "$+$", "$*$", and "$**$"

  - Add "(((" in the beginning of the expression (and hence before every "(" in the expression)
  - Add ")))" at the end of the expression (and hence after every ")" in the expression)
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- Our expression becomes fully parenthesized by application of this rule.

$$A \quad + \quad B ** C \quad * \quad (D \quad + \quad E)$$

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Uday Khedker
IIT Bombay

Talk Title:
History of Compiling

Topic:
Outline

What is a Compiler?

The Birth of a Compiler

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(The rules can be applied in a single left-to-right scan of the expression)

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- How about the same precedence for "/" and "$*$" and left associativity?
  - $n/2 * (n - 1)$
  - $n * (n - 1) * (1/2)$

FORTRAN Compiler Anecdotes (2)

On compiler reliability

- Tables stored on the magnetic drum based memory
- Slow searches and more load on drums
- The compiler worked far better at GM than at Westinghouse
- GM people had ensured a much better servicing of magnetic drums!

FORTRAN Compiler Anecdotes (3)

On compiler efficiency

- Frank Engel at Westinghouse observed that tapes moved independently but sequentially
- Compiler could become faster if tape movement is made to overlap
- Frank asked for the source and got a reply: (source meant assembly)

  "IBM does not supply source code"
- Frank patched up the octal object code of the compiler and the throughput increased by a factor of 3!
- IBM was surprised and wanted a copy, so Frank said:

  "Westinghouse does not supply object code"

A FORTRAN Program for Array Copy

Program

```
      DIMENSION A (10,10)
      DIMENSION B (10,10)

      DO 1 J = 1, 10
      DO 1 I = 1, 10
1     A(I,J) = B(I,J)
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A simplified view for 4x3 fragments

B(1,1)	B(1,2)	B(1,3)
B(2,1)	B(2,2)	B(2,3)
B(3,1)	B(3,2)	B(3,3)
B(4,1)	B(4,2)	B(4,3)

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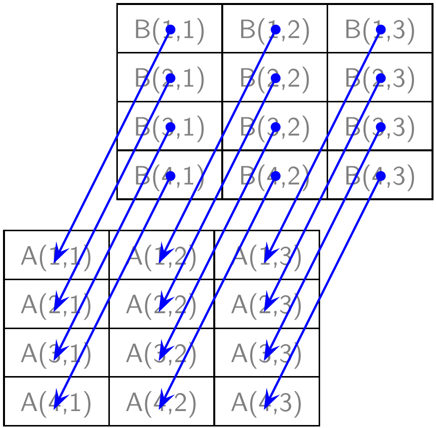

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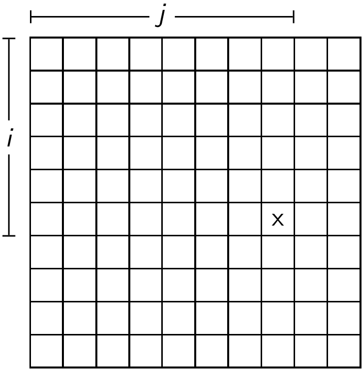
Array Address Calculation

Cell (i, j)

Its address



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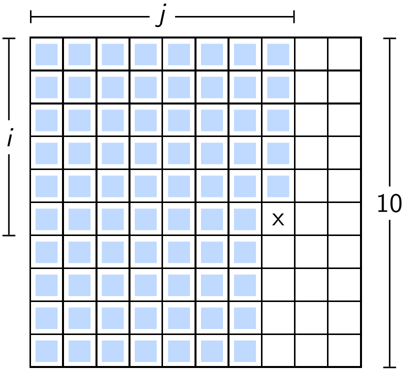

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$$\text{Base} + (j - 1) * 10 + i - 1$$

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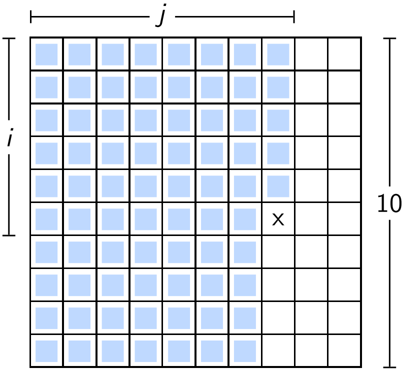

$$\text{Base} + (j - 1) * 10 + i - 1$$

An additional complication: In FORTRAN, arrays are stored backwards and index registers are subtracted from the base

Output of FORTRAN I Compiler

Source Program

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```

Object Program

	Statement	Explanation
	LXD ONE, 1	$Ixr1 = 1$
LOOP	CLA B+1, 1	$Acc = *(B + 1 - Ixr1)$
	STO A+1, 1	$*(A + 1 - Ixr1) = Acc$
	TXI * +1, 1, 1	$Ixr1 = Ixr1 + 1$, jump ahead by 1
	TXL LOOP,1 ,100	if ($Ixr1 \leq 100$), goto LOOP

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- Address calculation?
- Nested loops?

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Compiling Array Copy Program Using GCC 4.7.2 (gfortran)

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.L5:
        leal     408(%esp), %ebx
        movl     $1, %eax
        leal     808(%esp), %ecx
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        .p2align 4,,7
        .p2align 3
.L4:
        movl     -44(%ecx,%eax,4), %edx
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        addl     $1, %eax
        cmpl     $11, %eax
        jne      .L4
        addl     $40, %esi
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- Integer is now 4 bytes

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- Integer is now 4 bytes
- Efficient address calculation with strength reduction
- Nested loops not flattened

Modern Challenges

The Sources of New Challenges

- Languages have changed significantly
- Processors have changed significantly
- Problem sizes have changed significantly
- Expectations have changed significantly
- Analysis techniques have changed significantly

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- P
- P
- E

Full Employment Guarantee Theorem for Compiler Writers

(https://en.wikipedia.org/wiki/Full_employment_theorem)

The notion of "best" compiler cannot exist and there is endless scope to keep improving

$\Rightarrow$ For every compiler, a better compiler can be written

- Analysis techniques have changed significantly
    - Parsing, Data flow analysis, Parallism Discovery, Heap Analysis

Modern Challenges: Target Machine Issues

How to exploit

- Pipelines? (Spectre bug)
- Multiple execution units (pipelined)
- Cache hierarchy
- Parallel processing
  (Shared memory, distributed memory, message-passing)
- Vector operations
- VLIW and Superscalar instruction issue

General strategy: Hardware software co-design

Modern Challenges: Target Machine Issues

How to exploit

- Pipelines? (Spectre bug)
- Multiple execution units (pipelined)

The crux of the matter

- Hardware is parallel, (conventional) software is sequential
- Software view is stable, hardware is disruptive

General strategy: Hardware software co-design

Modern Challenges: New Expectations

- New application domains bringing new challenges
- What are the underlying abstractions of the domains that should become first class citizens in a programming language?
  - Language design and compilers for machine learning algorithms?
  - Language design and compilers for streaming applications?
- Can machine learning algorithms help compilers create new optimizations?
  - Can human ingenuity in design of novel algorithms be replaced by machine learning?
    Need explanability for guaranteeing soundess of new optimizations
    Known cost based optimizations have a better chance with machine learning
  - Can compilers learn from the programs they have compiled and become “better” over time?

Conclusions

The Wonder Element of FORTRAN

- Expressiveness Vs. Efficiency conflict
  - Efficiency of programming and reach of programming, OR
  - Efficiency of program execution and resource utilization
- FORTRAN: The triumph of the genius of AND over the tyranny of OR

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  - Efficiency of programming and reach of programming, OR
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- FORTRAN: The triumph of the genius of AND over the tyranny of OR
- *The software equivalent of a transistor*

The Challenge Ahead

- Expressiveness Vs. Efficiency conflict due to the problem of scale

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- Expressiveness Vs. Efficiency conflict due to the problem of scale
- Have we reached the Von Neumann bottleneck?

  Backus argued so over three decades ago!
- At an abstract level, the status of compilers is similar to those in the John Backus era
  - Architectures not understood well enough for exploitation by compilers
  - Architecturs influencing language features
  - Comparison with assembly
  - No past success story

Intersting Reads Available Online

- *Computer History Museum* (`www.computerhistory.org`)
  - FORTRAN examples by John Backus
  - Array copy example by Frances Allen
  - FORTRAN expression handling explanation by David Padua
- "Is Code Optimization Research Relevant," Bill Pugh (2000)
- "The Death of Optimizing Compilers," Daniel Bernstein (2015)
- "What Challenges and Trade-Offs do Optimising Compilers Face?" Laurence Tratt (2017)
- "The Correctness-Security Gap in Compiler Optimization," V. D'Silva, M. Payer and D. Song (2015)
- Proceedings of the *History of Programming Languages* conferences: `https://dl.acm.org/conference/hopl/proceedings`

Uday Khedker
IIT Bombay

The Moral of the Story

Achieving Performance

Expressiveness (Rich abstractions)
Generality (Retargetability, upgrades and enhancements)
Providing Guarantees (Correctness, robustness, security)

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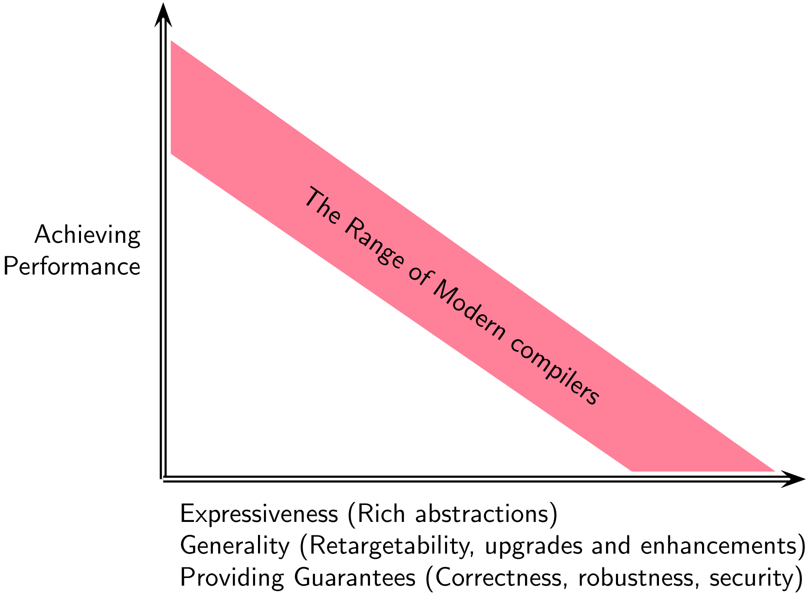

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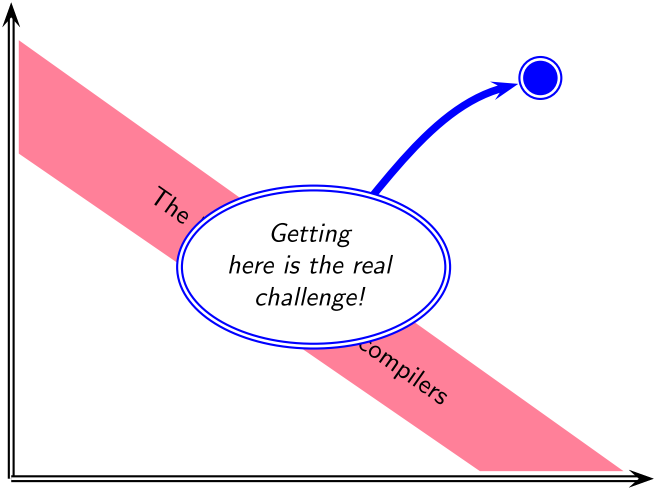

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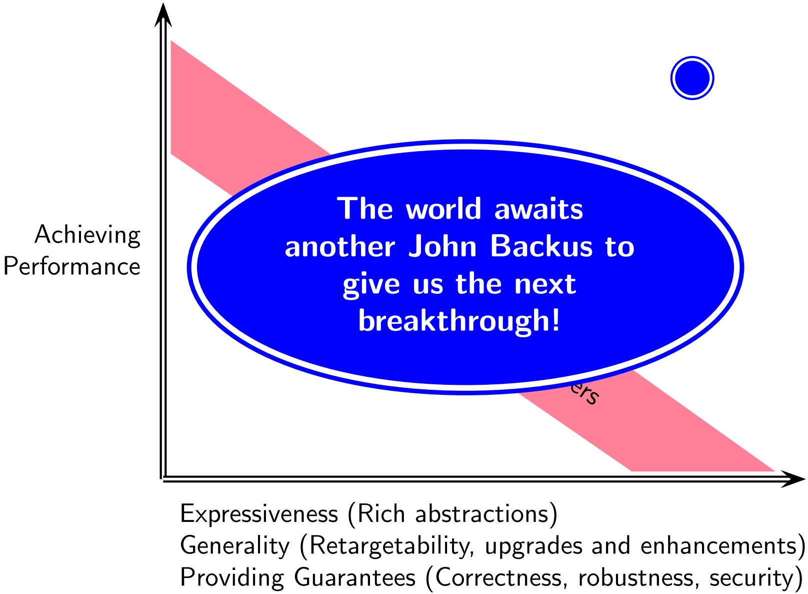

Last But Not the Least

Thank You!

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Contacting me :

- `uday@cse.iitb.ac.in`
- `http://www.cse.iitb.ac.in/~uday`