Challenges in Compiling: Past, Present, and Future

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Outline

- What is a compiler?
- The biggest challenge: The Birth of a compiler
- The structure of modern compilers
- Modern challenges
- Conclusions

What is a Compiler?

Implementation Mechanisms

Source Program

↓

Translator

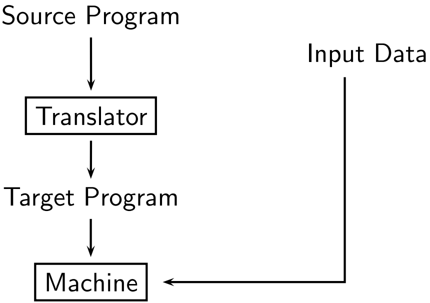
↓

Target Program

↓

Machine

Implementation Mechanisms



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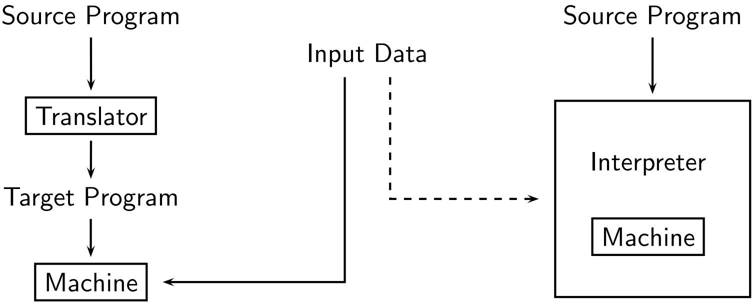

Implementation Mechanisms as "Bridges"

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

Program Specification

Machine

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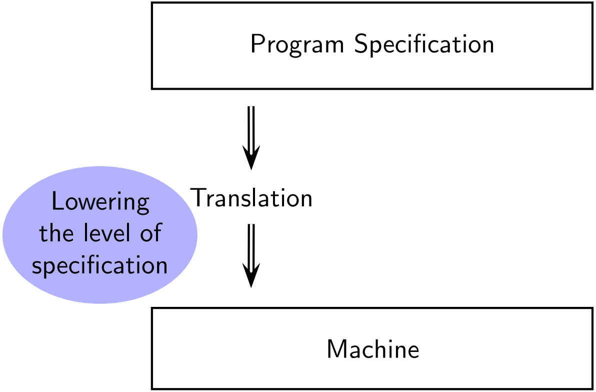

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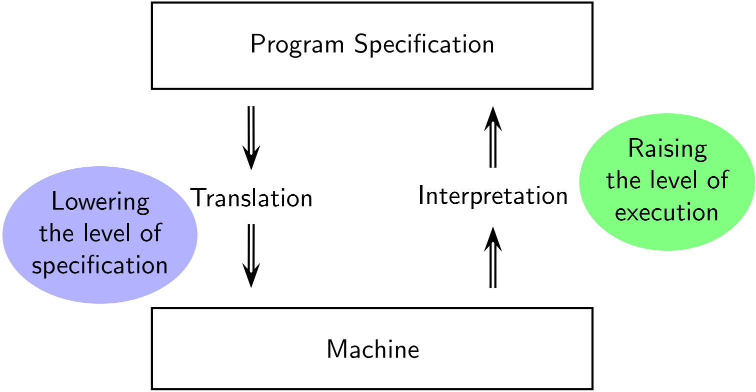

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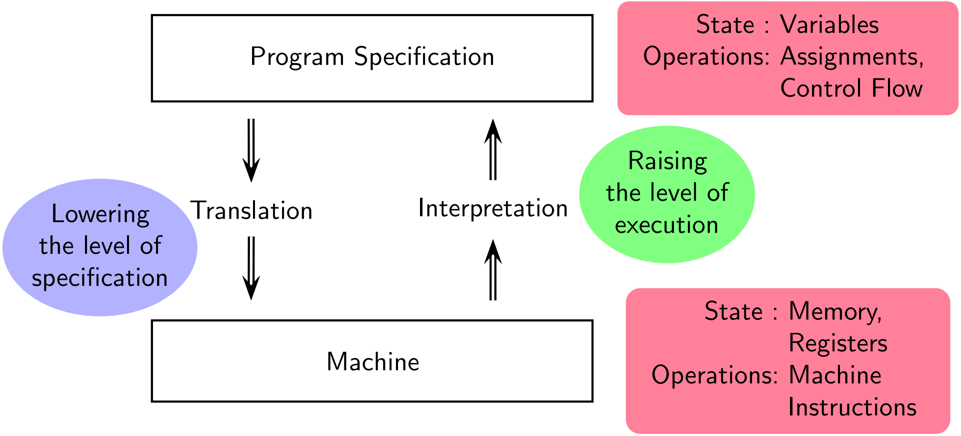

A Source Program in C++: High Level Abstraction

```
#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

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  Writing programs whose data is programs
- The beauty and enormity of compiling lies in
    - Raising the level of abstraction and bridging the gap without performance penalties
    - Meeting the expectations of users with a wide variety of needs

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

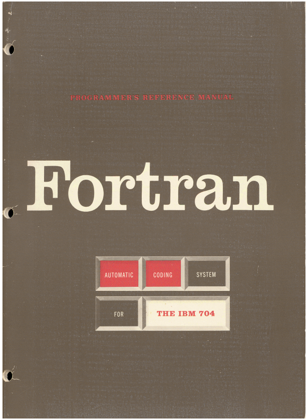

Image Source: Wikipedia

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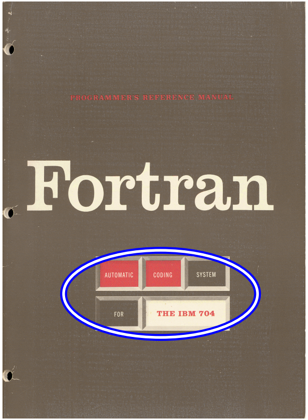

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Pioneers of Programming Languages (Knuth-Pardo, 1976)

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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
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- *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."*

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

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

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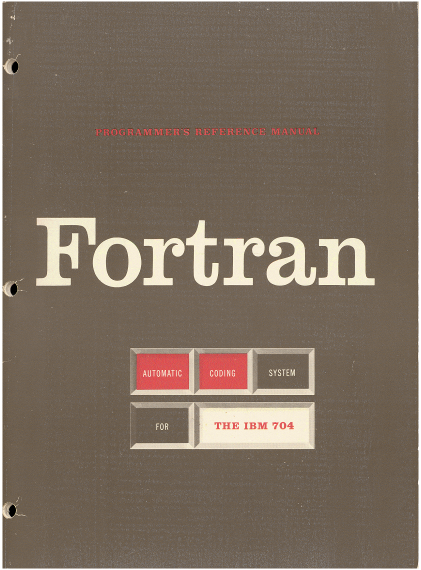
FORTRAN Claims (2)

"FORTRAN will virtually eliminate coding and debugging"

☺



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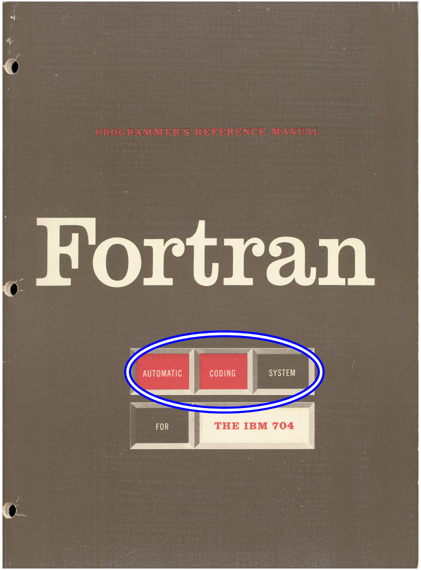

Limitations of FORTRAN I Language

- 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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- 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

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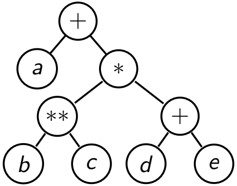
Expressions in the Programs

- 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
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- Our expression becomes fully parenthesized by application of this rule.

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IIT Bombay

Talk Title:
Compiling-Challenges

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

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

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  - For $n = 10$, the expression $n * (n - 1)/2$ computed 40 instead of 45!

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  - $n/2 * (n - 1)$
  - $n * (n - 1) * (1/2)$

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
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A simplified view for 4x3 fragments

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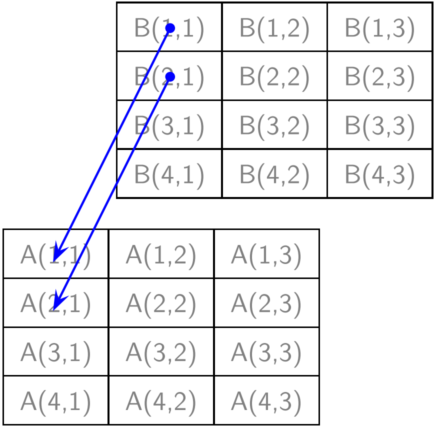

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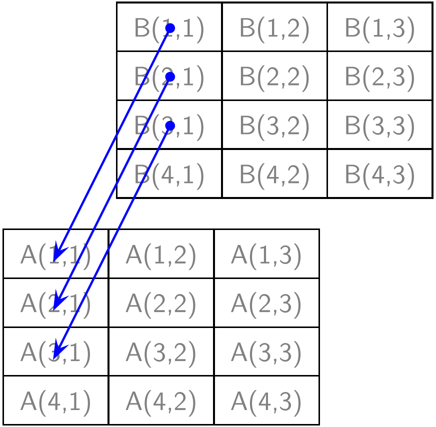

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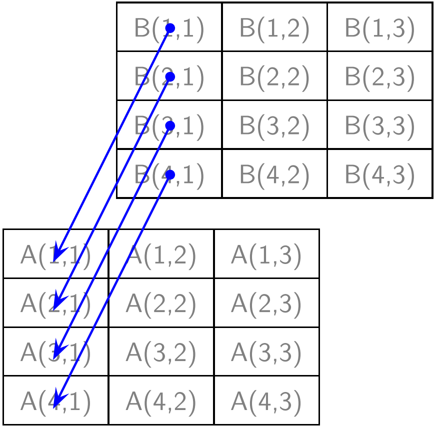

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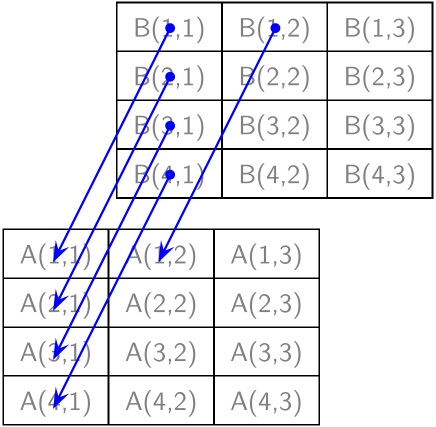

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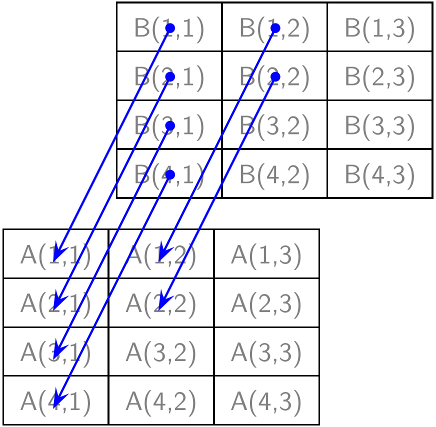

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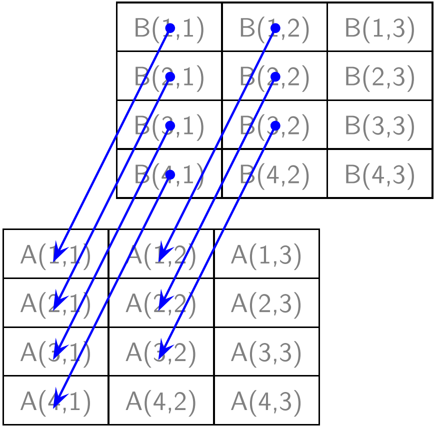

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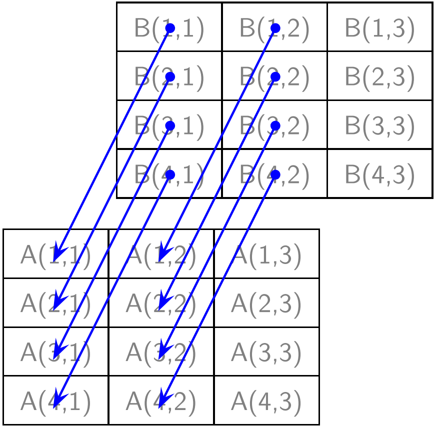

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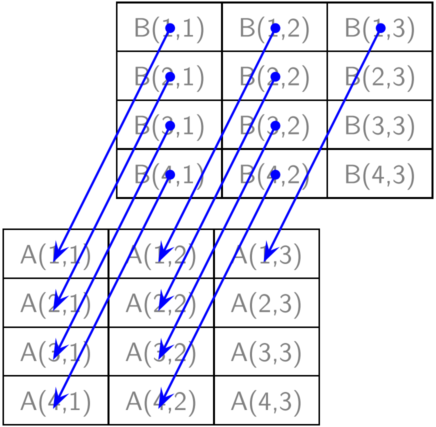

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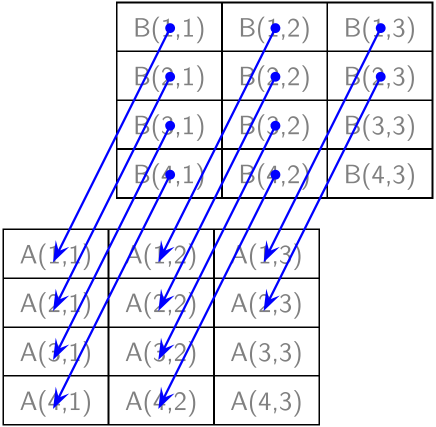

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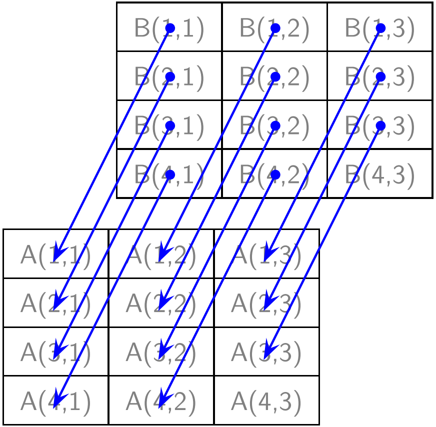

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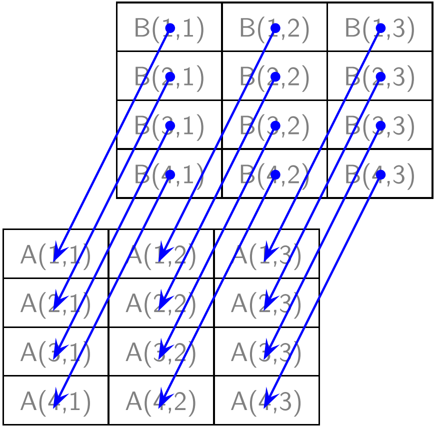

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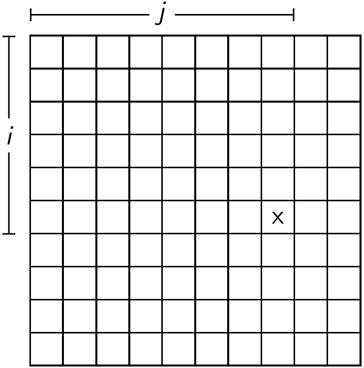
Array Address Calculation

Cell (i, j)

Its address



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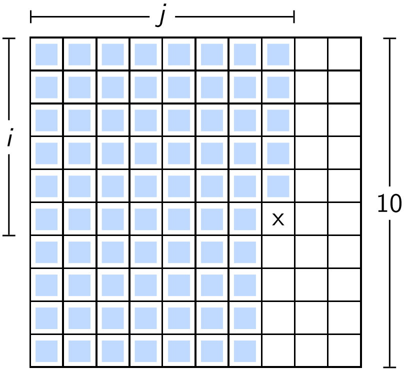

$$\text{Base} + (j-1) * 10 + i - 1$$

Array Address Calculation

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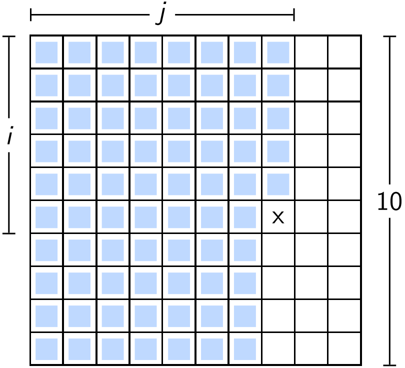

$$\text{Base} + (j-1) * 10 + i - 1$$

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

Output of FORTRAN I Compiler

Source Program

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

      DO 1 J = 1, 10
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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: Control Flow Graph

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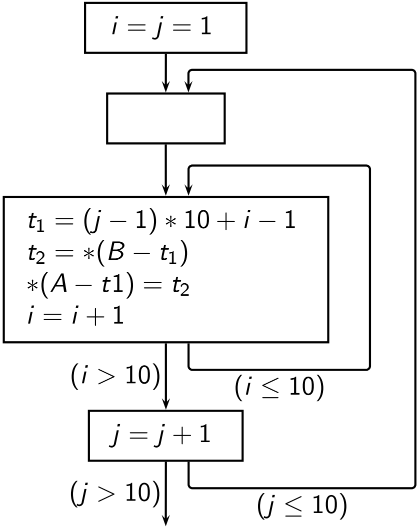
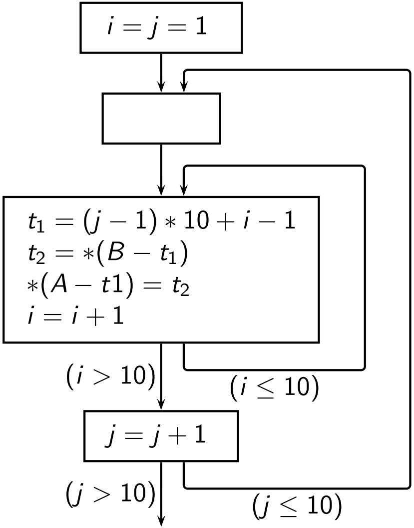


Compiling Array Copy Program: Strength Reduction (1)



Observations about the inner loop

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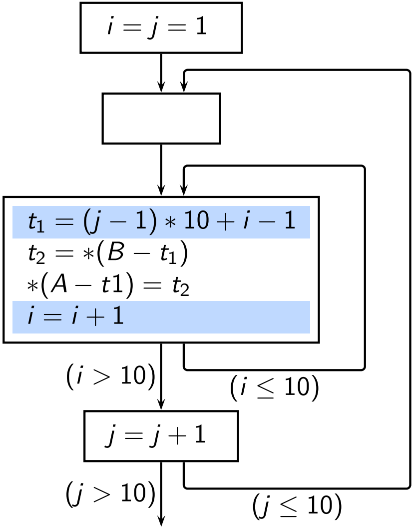

Observations about the inner loop

- Whenever i increments by 1, $t1$ also increments by 1

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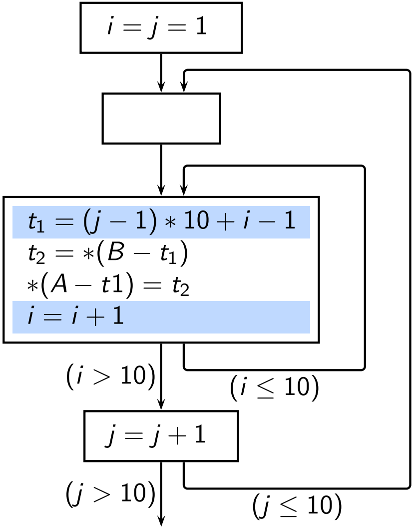

Observations about the inner loop

- Whenever i increments by 1, $t1$ also increments by 1
- We can initialize $t1$ outside of the inner loop

  $$\begin{aligned} t1 &= (j-1)*10+i-1 \\ &= (j-1)*10 \\ &\ \text{(because } i \text{ is 1)} \end{aligned}$$

  and increment it within the loop

  $t1 = t1 + 1$

Compiling Array Copy Program: Strength Reduction (2)

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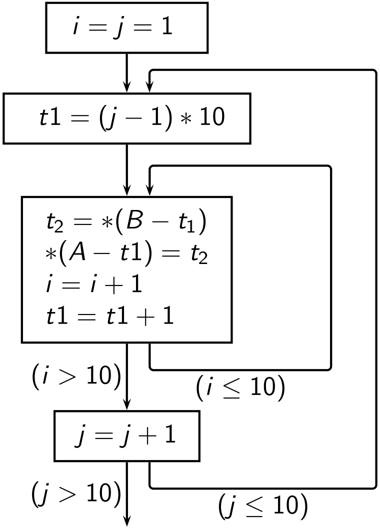

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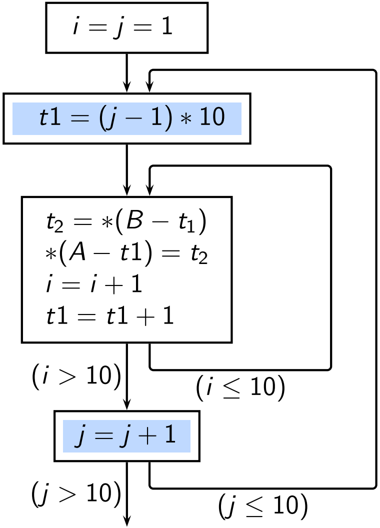
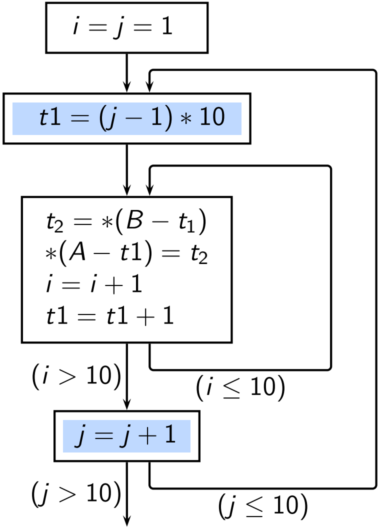


Observations about the inner loop

- Whenever j increments by 1, $t1$ increments by 10

Compiling Array Copy Program: Strength Reduction (2)



Observations about the inner loop

- Whenever j increments by 1, $t1$ increments by 10
- We can initialize t1 outside of the outer loop

$$\begin{aligned} t1 &= (j-1) * 10 \\ &= 0 \\ &\ \text{(because } j \text{ is 1)} \end{aligned}$$

and increment it within the loop

$t1 = t1 + 10$

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IIT Bombay

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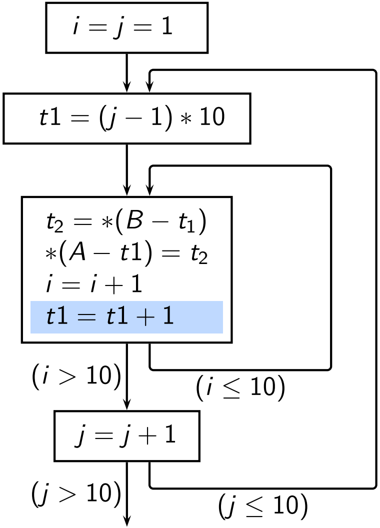

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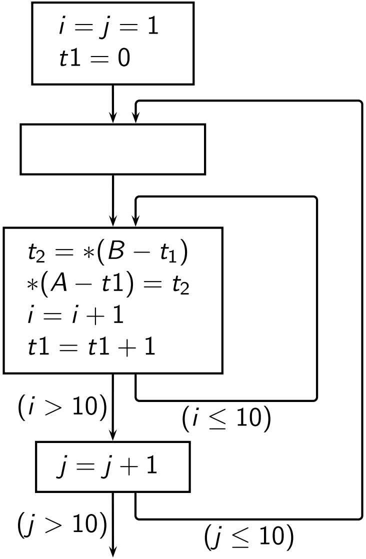
  $$\begin{aligned} t1 &= (j-1) * 10 \\ &= 0 \\ &\quad \text{(because } j \text{ is 1)} \end{aligned}$$

  and increment it within the loop

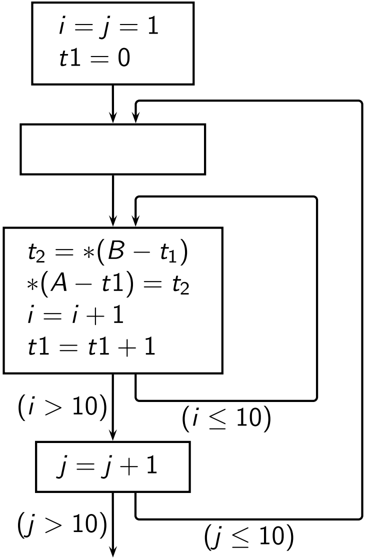
  $$t1 = t1 + 10$$

- However, the inner loop already increments $t1$ by 10.

Compiling Array Copy Program: Flattening the Loops



Compiling Array Copy Program: Flattening the Loops



- The only activity in the outer loop now is to control the loop iterations

  No other computation

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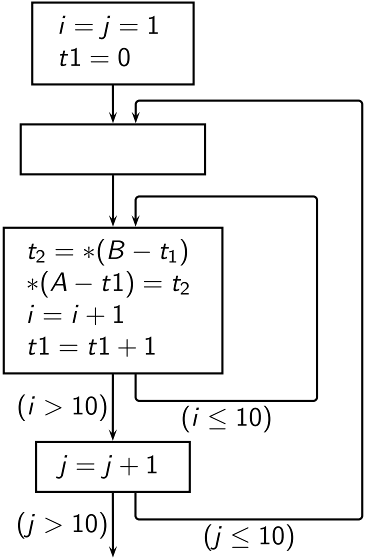
Compiling Array Copy Program: Flattening the Loops



- The only activity in the outer loop now is to control the loop iterations

  No other computation
- We can combine the loops into a single loop by taking a product of the two loop bounds
- Variables i and j would not be required

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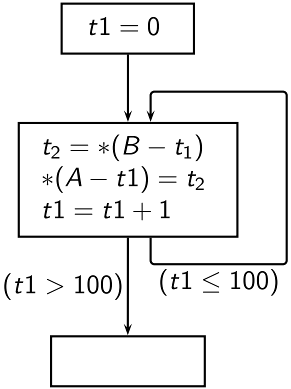
Compiling Array Copy Program: The Final Program

Control flow graph (CFG)	Original Assembly
	

Compiling Array Copy Program: The Final Program

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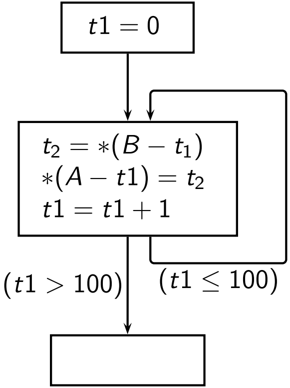
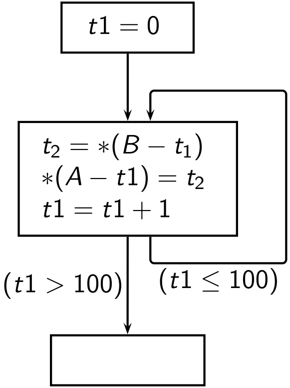
Control flow graph (CFG)	Original Assembly
	see below


```
      LXD ONE, 1
LOOP  CLA B+1, 1
      STO A+1, 1
      TXI * +1, 1, 1
      TXL LOOP,1 ,100
```

Compiling Array Copy Program: The Final Program

Control flow graph (CFG)	Original Assembly




```
      LXD ONE, 1
LOOP  CLA B+1, 1
      STO A+1, 1
      TXI * +1, 1, 1
      TXL LOOP,1 ,100
```

Minor differences

	CFG	Assembly
Base address	B	$B + 1$
Initial value of $t1$	0	1

Compiling Array Copy Program Using GCC 4.7.2 (gfortran)

```
.L5:
        leal    408(%esp), %ebx
        movl    $1, %eax
        leal    808(%esp), %ecx
        addl    %esi, %ebx
        addl    %esi, %ecx
        .p2align 4,,7
        .p2align 3
.L4:
        movl    -44(%ecx,%eax,4), %edx
        movl    %edx, -44(%ebx,%eax,4)
        addl    $1, %eax
        cmpl    $11, %eax
        jne     .L4
        addl    $40, %esi
        cmpl    $400, %esi
        jne     .L5
```

- Integer is now 4 bytes

Compiling Array Copy Program Using GCC 4.7.2 (gfortran)

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```
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- Integer is now 4 bytes
- Efficient address calculation with strength reduction

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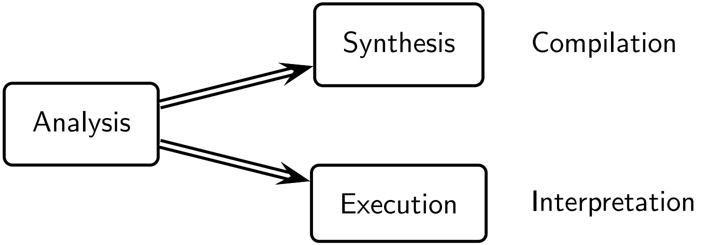
        jne      .L5
```

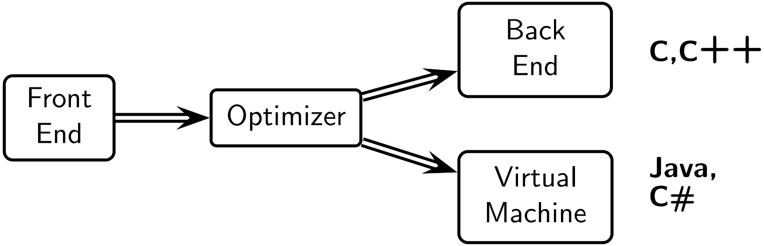
- Integer is now 4 bytes
- Efficient address calculation with strength reduction
- Nested loops not flattened

The Structure of Modern Compilers

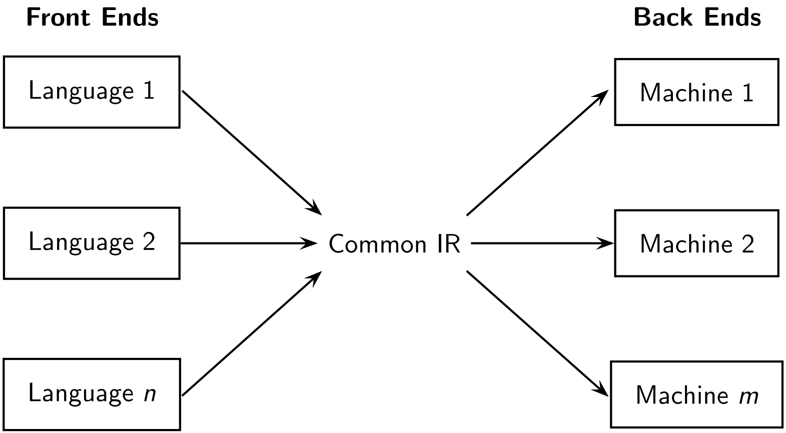
Language Implementation Models



Language Processor Models



Reusability of Language Processor Modules



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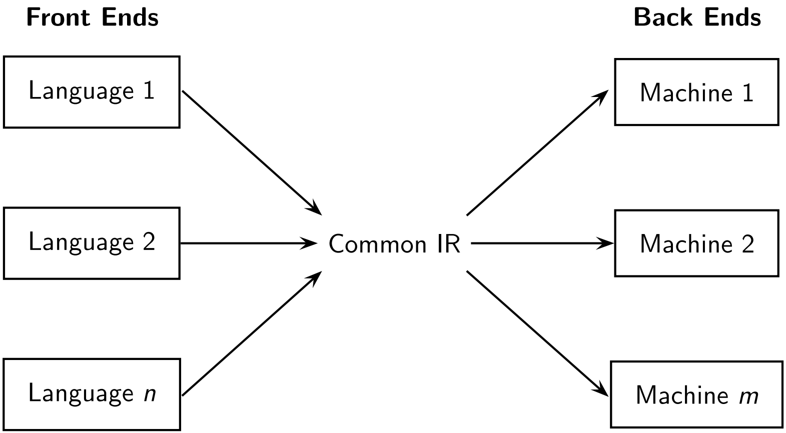


$m \times n$ compilers can be obtained from $m + n$ modules

Compilation Models

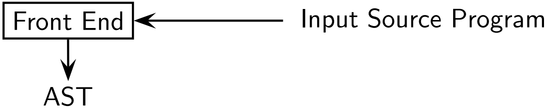
Aho Ullman Model

Davidson Fraser Model

Compilation Models

Aho Ullman Model

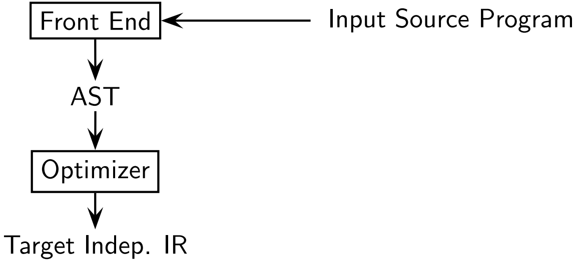
Davidson Fraser Model



Compilation Models

Aho Ullman Model

Davidson Fraser Model



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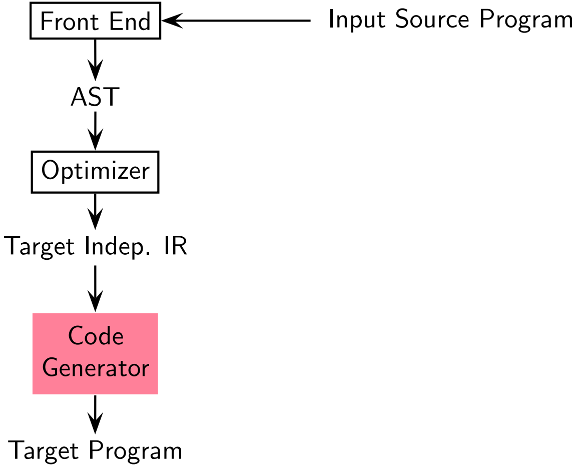

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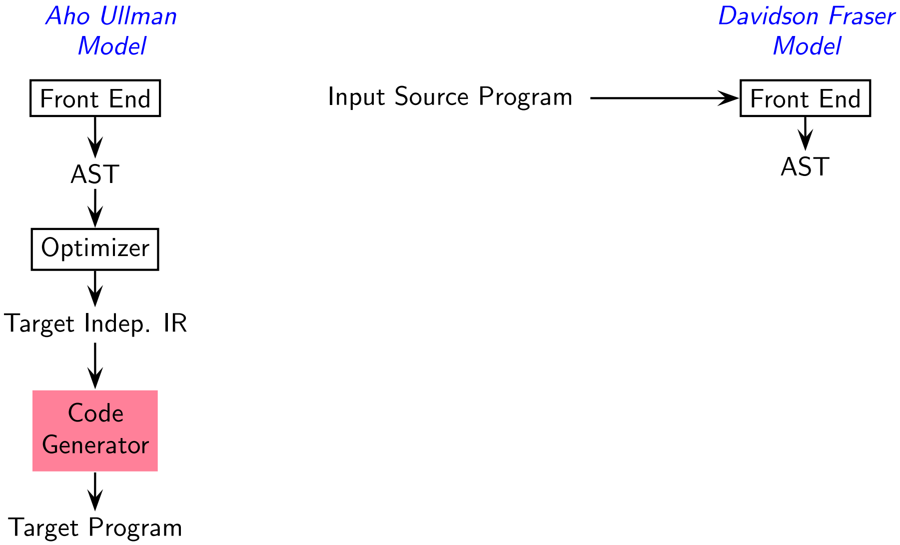

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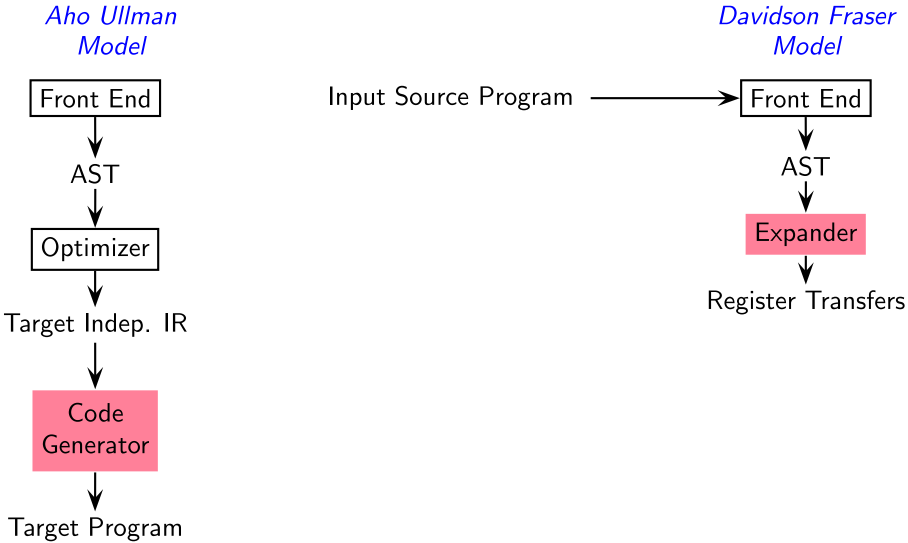

Compilation Models

Aho Ullman Model

Front End
↓
AST
↓
Optimizer
↓
Target Indep. IR
↓
Code Generator
↓
Target Program

Input Source Program →

Davidson Fraser Model

Front End
↓
AST
↓
Expander
↓
Register Transfers
↓
Optimizer
↓
Register Transfers

Compilation Models

Aho Ullman Model

Front End
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Optimizer
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Target Indep. IR
↓
Code Generator
↓
Target Program

Input Source Program →

Davidson Fraser Model

Front End
↓
AST
↓
Expander
↓
Register Transfers
↓
Optimizer
↓
Register Transfers
↓
Recognizer
↓
Target Program

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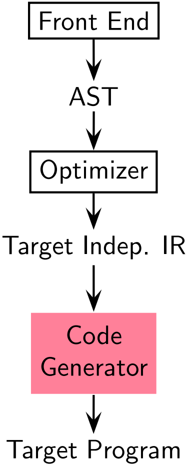
IIT Bombay

Compilation Models

Aho Ullman Model



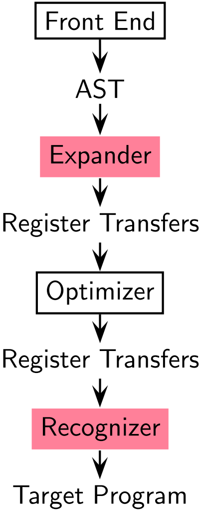
Aho Ullman: Instruction selection

- over optimized IR using
- cost based tree tiling matching

Davidson Fraser: Instruction selection

- over AST using
- simple full tree matching based algorithms that generate
- naive code which is
  - target dependent, and is
  - optimized subsequently

Davidson Fraser Model



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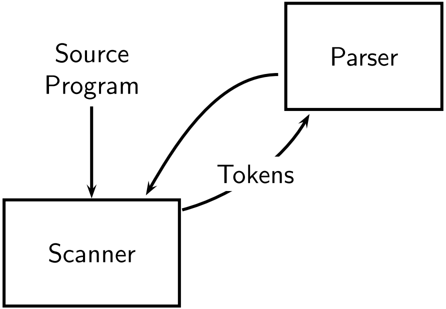
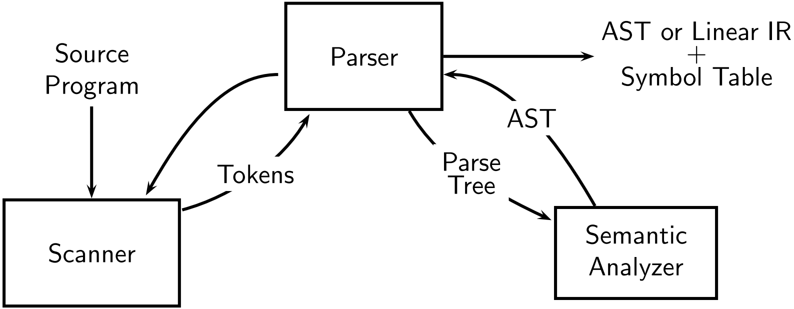
Typical Front Ends

Parser

Typical Front Ends



Typical Front Ends



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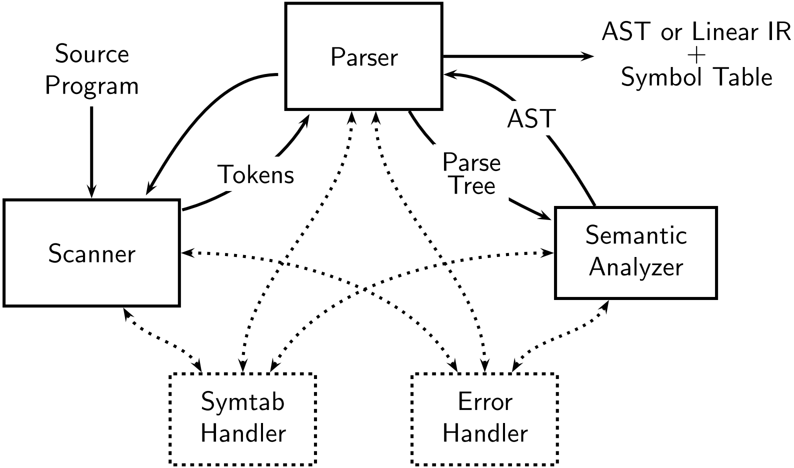

Typical Back Ends in Aho Ullman Model

m/c Ind. IR

m/c Ind. Optimizer

m/c Ind. IR

– Compile time evaluations
– Eliminating redundant computations

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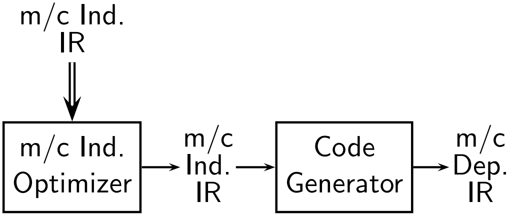
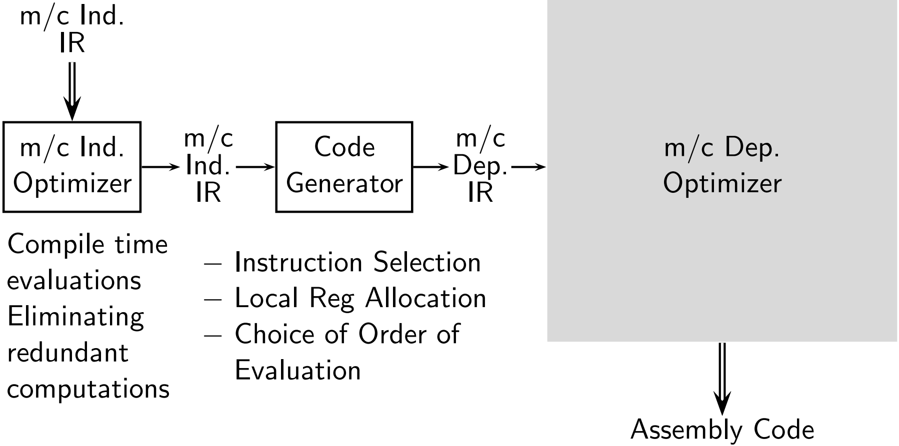
Typical Back Ends in Aho Ullman Model



- Compile time evaluations
- Eliminating redundant computations

- Instruction Selection
- Local Reg Allocation
- Choice of Order of Evaluation

Typical Back Ends in Aho Ullman Model



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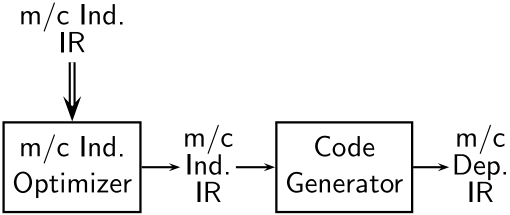

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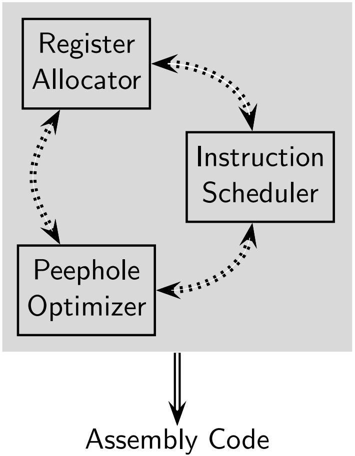
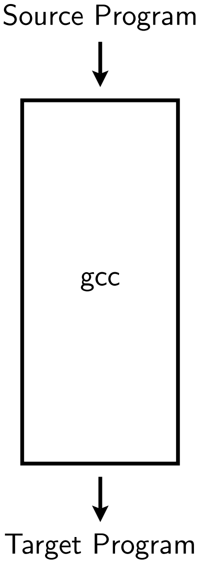


The GNU Tool Chain for C



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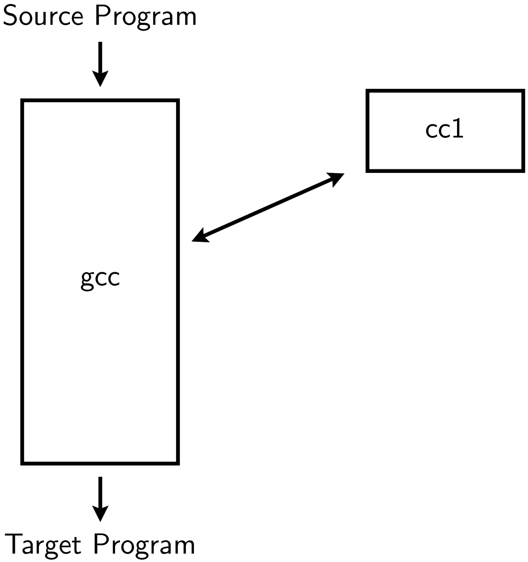

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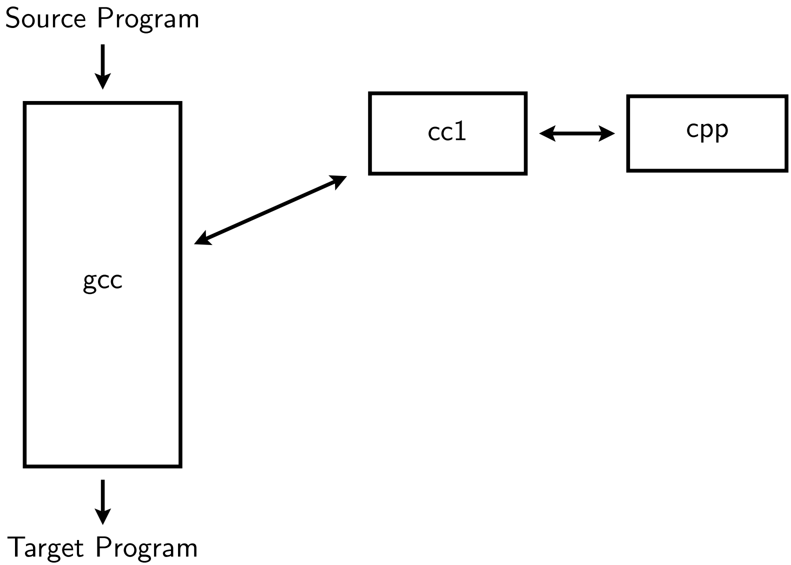

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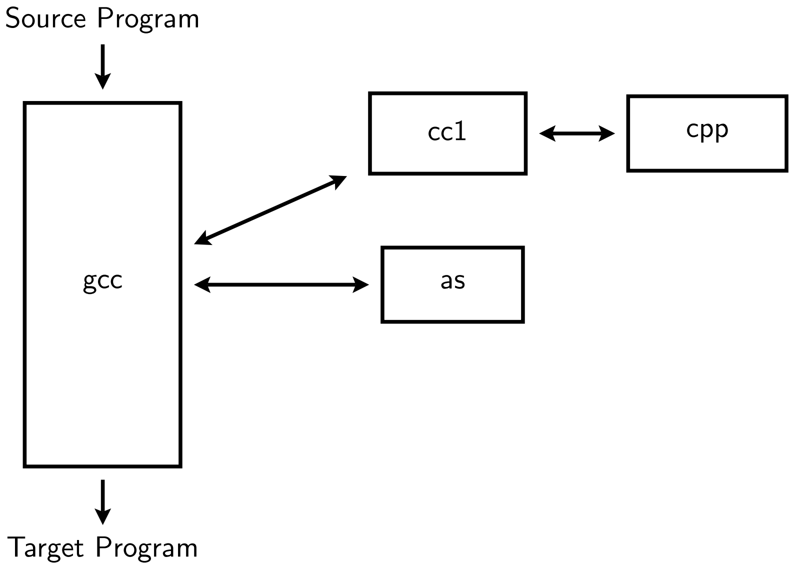

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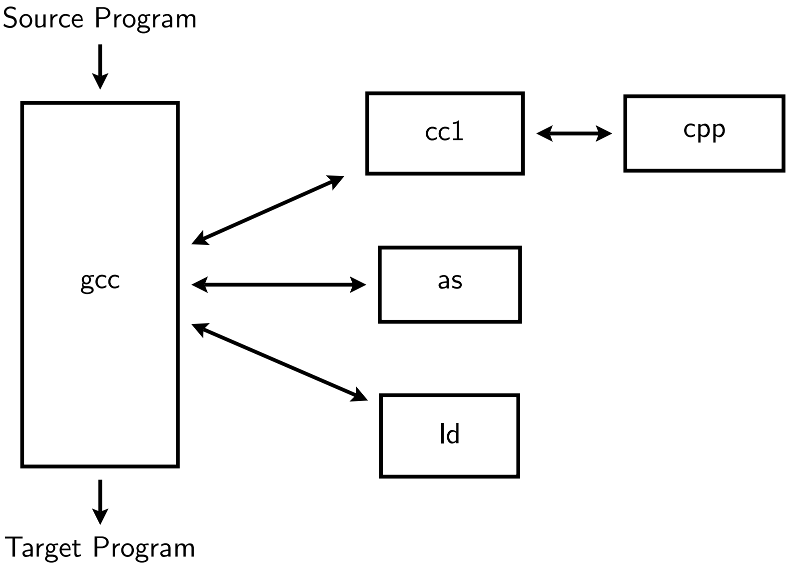

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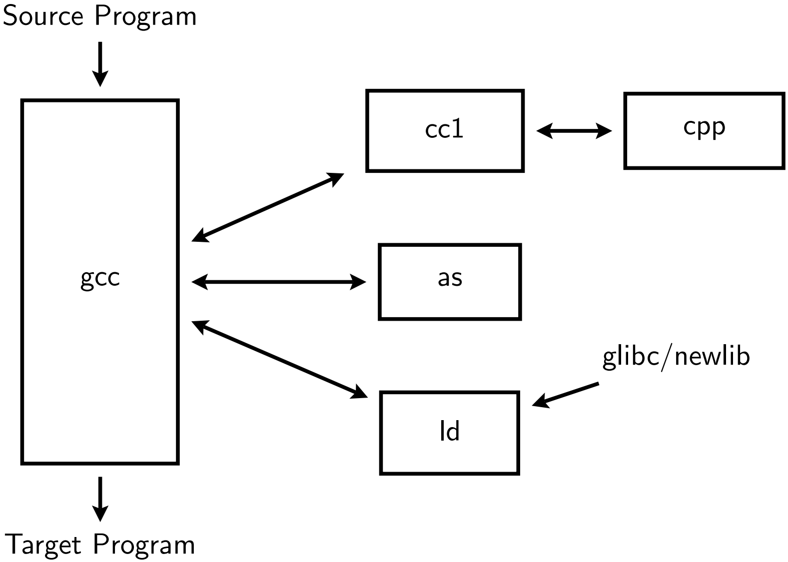

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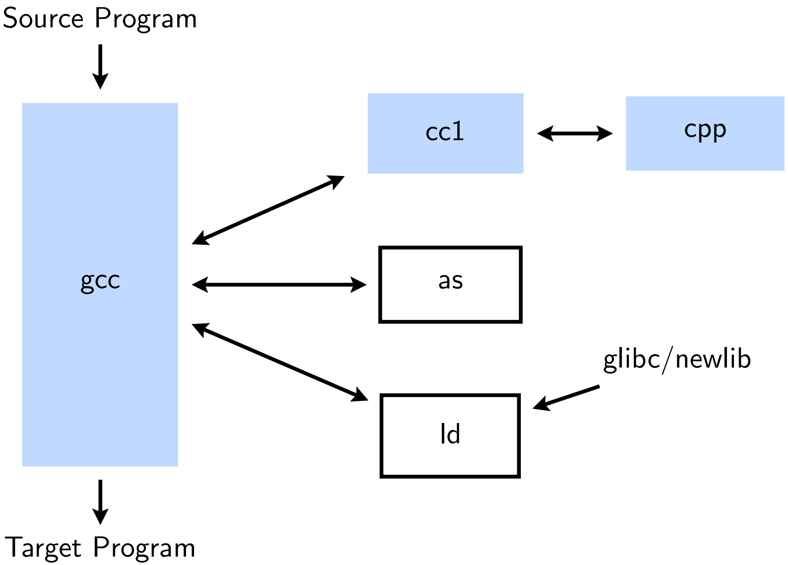

The Architecture of GCC

Compiler Generation Framework

Language Specific Code	Language and Machine Independent Generic Code	Machine Dependent Generator Code	Machine Descriptions

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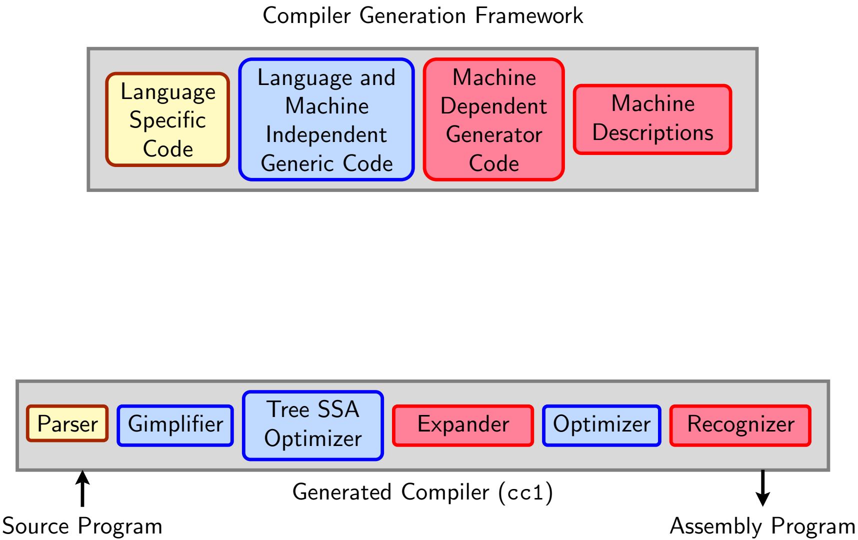
The Architecture of GCC



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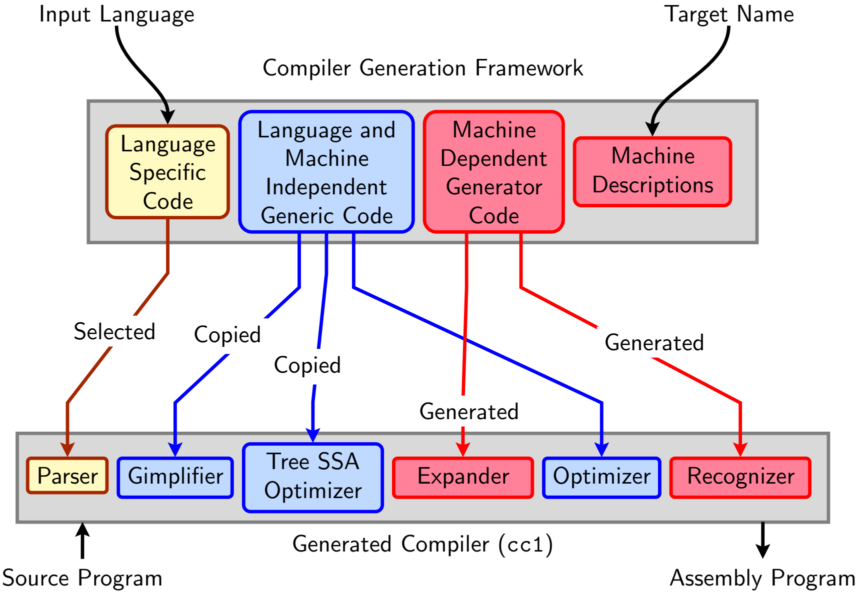

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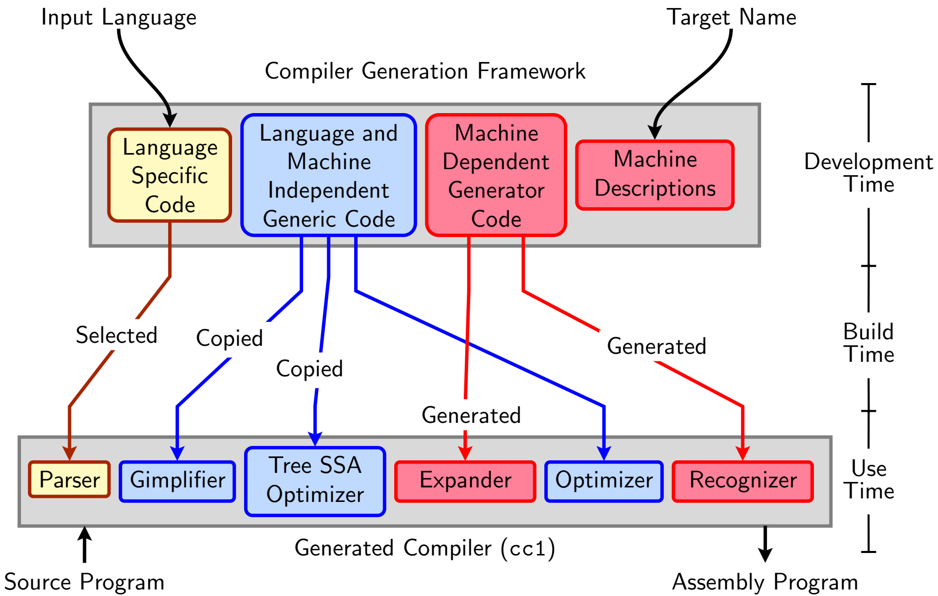
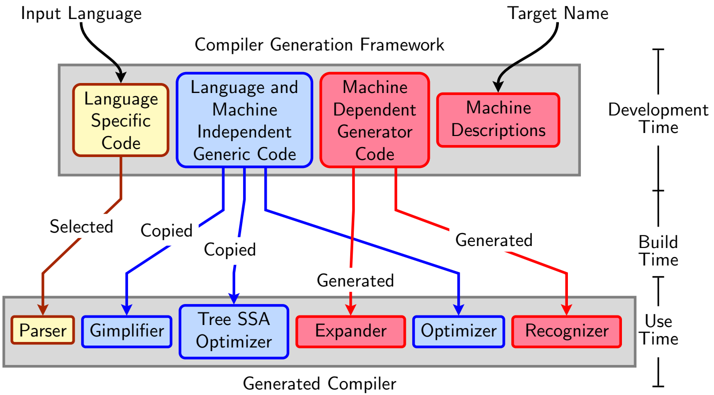


GCC Retargetability Mechanism



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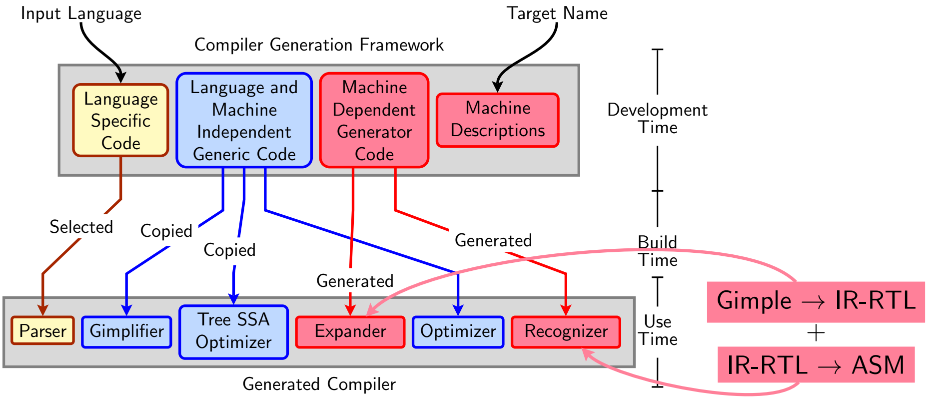

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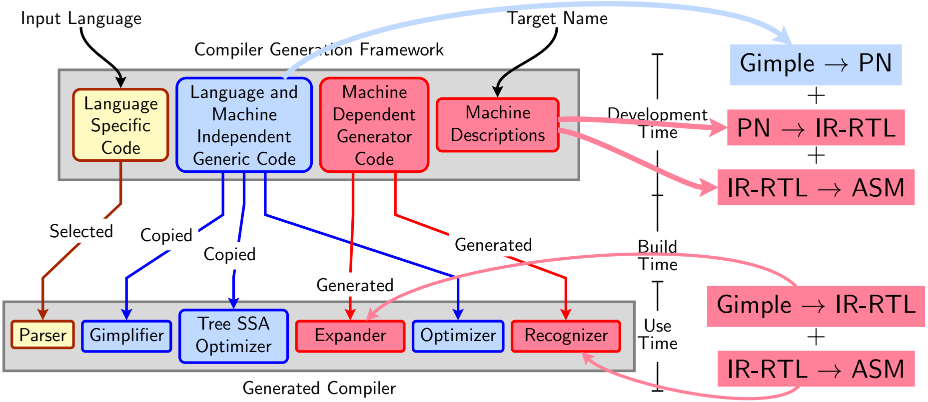
IIT Bombay

Talk Title:
Compiling-Challenges

Topic:

GCC Retargetability Mechanism



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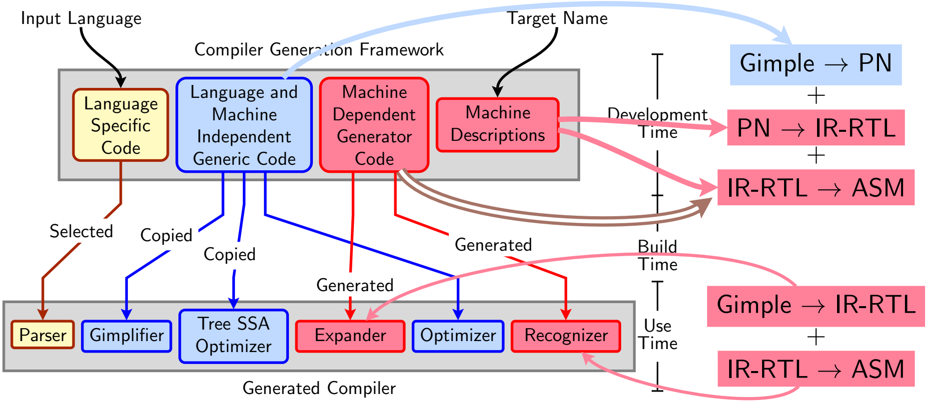

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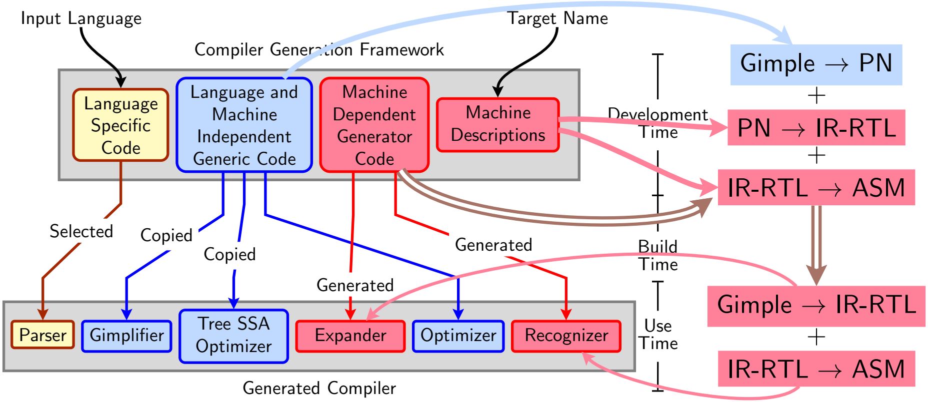

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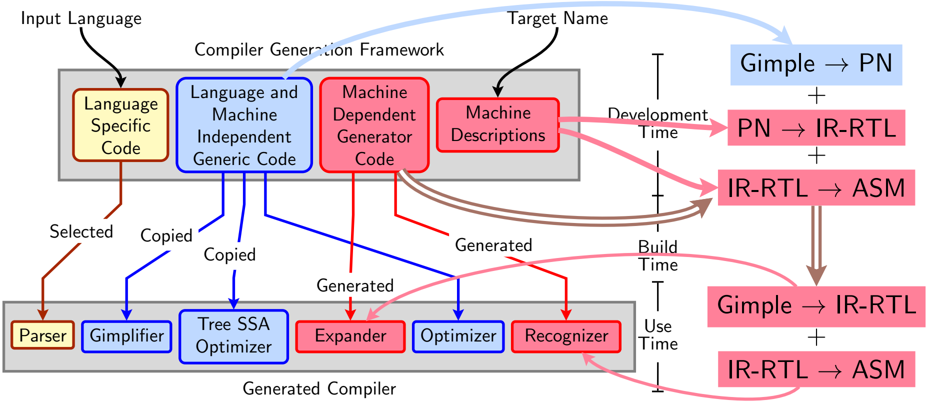
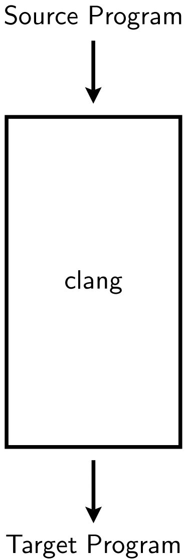


The generated compiler uses an adaptation of the Davidson Fraser model

- Generic expander and recognizer
- Machine specific information is isolated in data structures
- Generating a compiler involves generating these data structures

The LLVM Tool Chain for C



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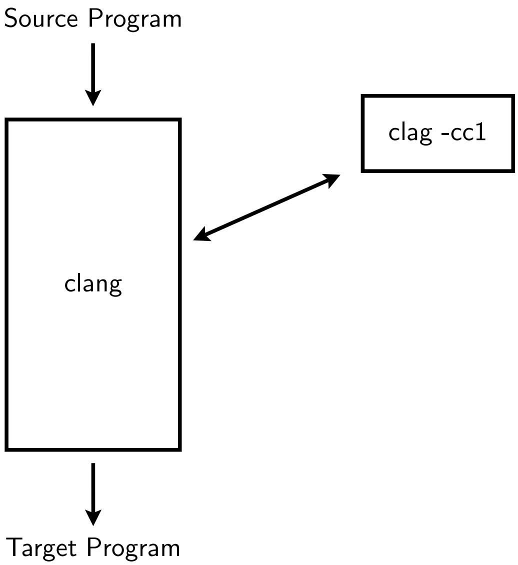

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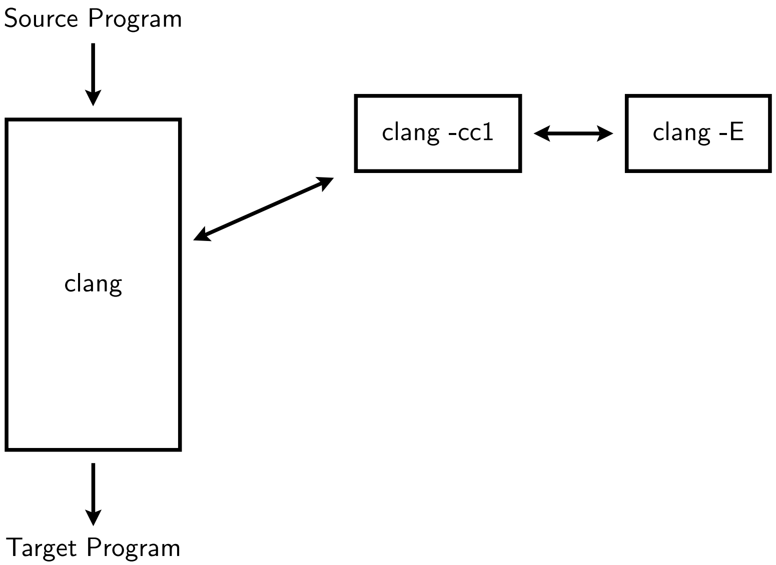

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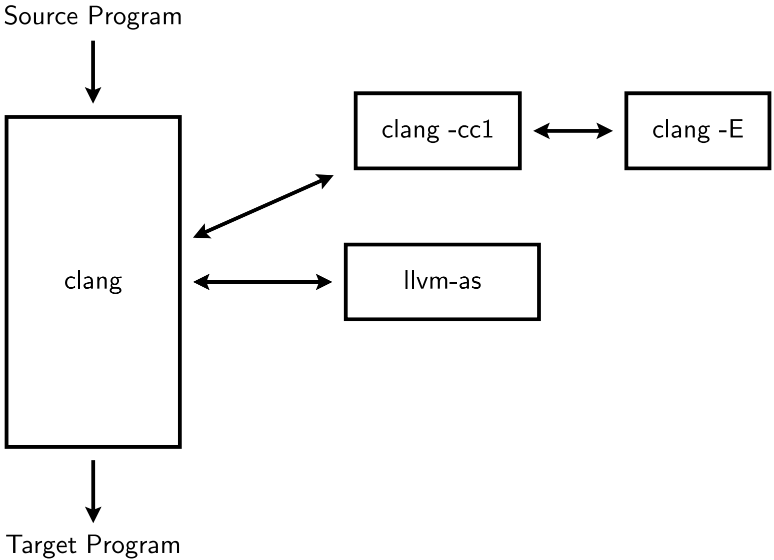

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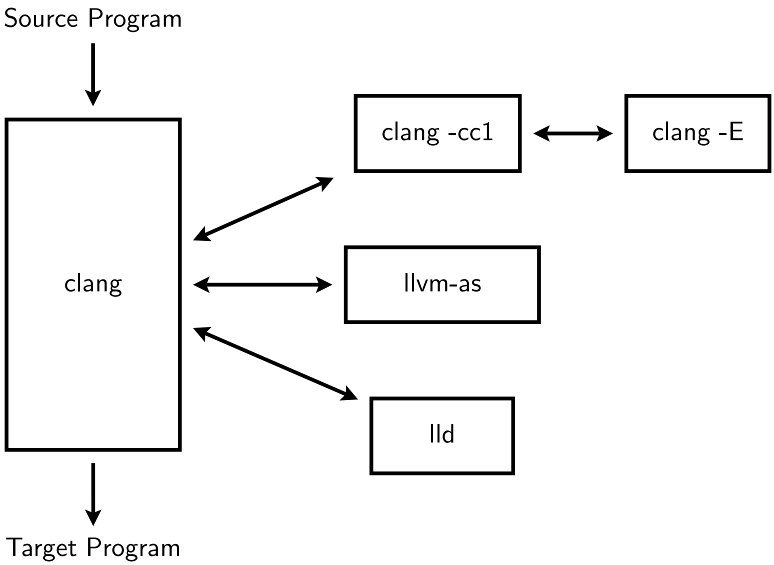

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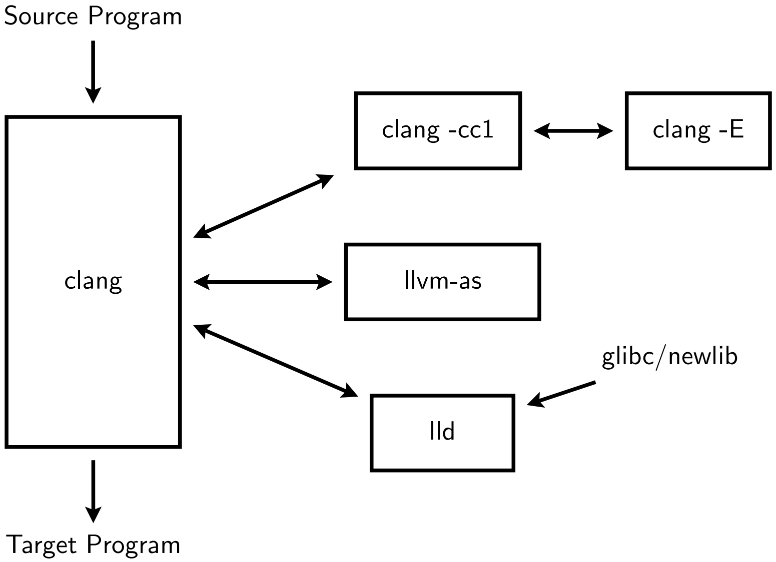

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IIT Bombay

Talk Title:
Compiling-Challenges

Topic:
Outline

What is a Compiler?

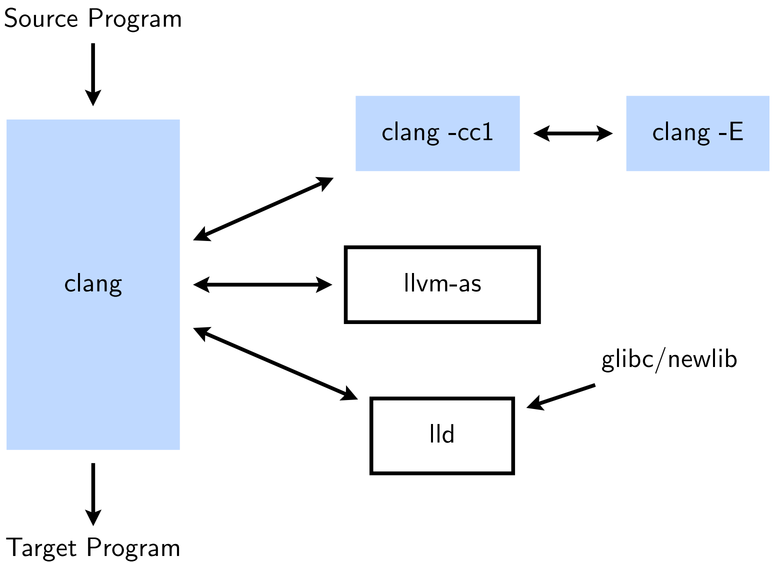
The Birth of a Compiler

The Structure of Modern Compilers

Modern Challenges

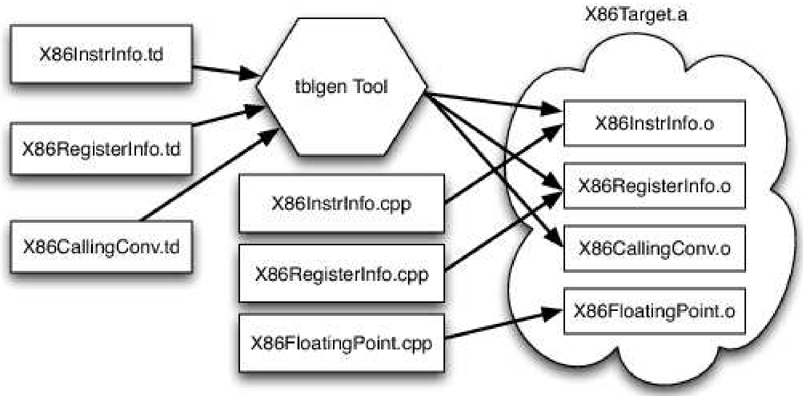
Conclusions

The LLVM Tool Chain for C



LLVM Retargetability Mechanism

Simplified x86 Target Definition



Reproduced from https://www.aosabook.org/en/llvm.html

Building a Compiler: Terminology

- The sources of a compiler are compiled (i.e. built) on *Build system*, denoted BS.
- The built compiler runs on the *Host system*, denoted HS.
- The compiler compiles code for the *Target system*, denoted TS.

The built compiler itself runs on HS and generates executables that run on TS.

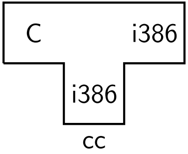
Variants of Compiler Builds

BS = HS = TS	Native Build
BS = HS ≠ TS	Cross Build
BS ≠ HS ≠ TS	Canadian Cross

Example

Native i386: built on i386, hosted on i386, produces i386 code.
Sparc cross on i386: built on i386, hosted on i386, produces Sparc code.

T Notation for a Compiler



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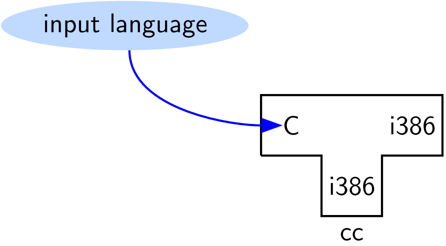

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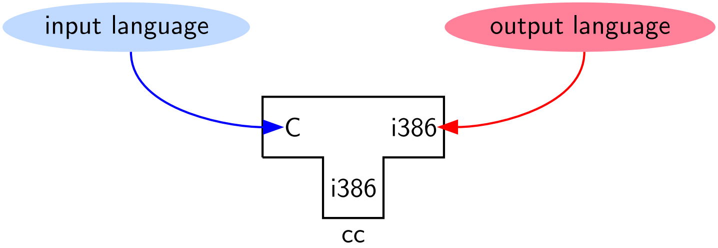

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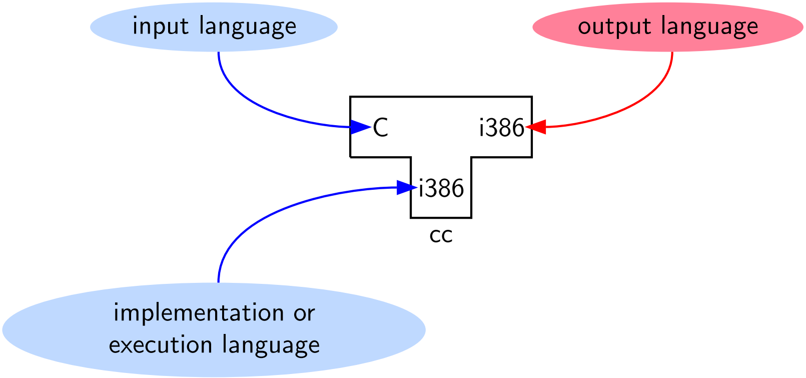

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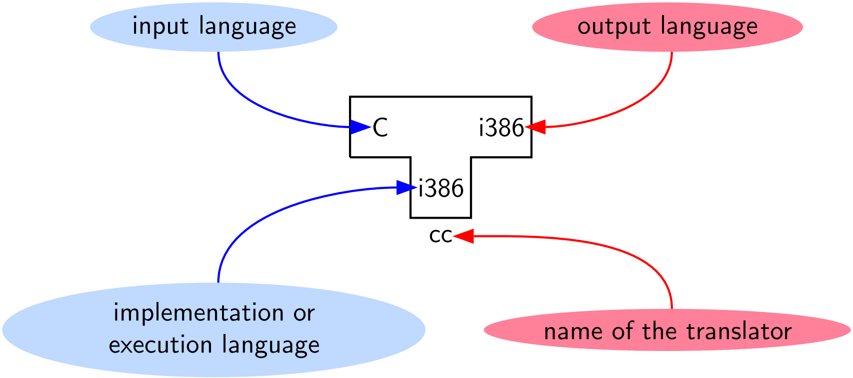
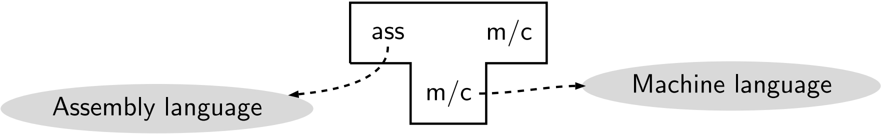


Bootstrapping: The Conventional View



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IIT Bombay

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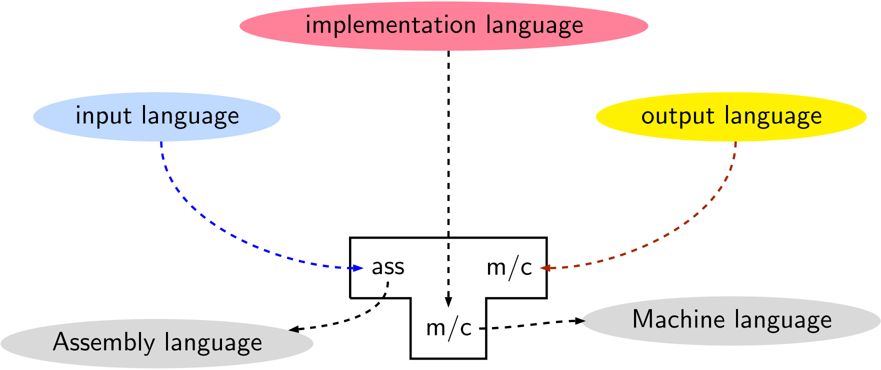

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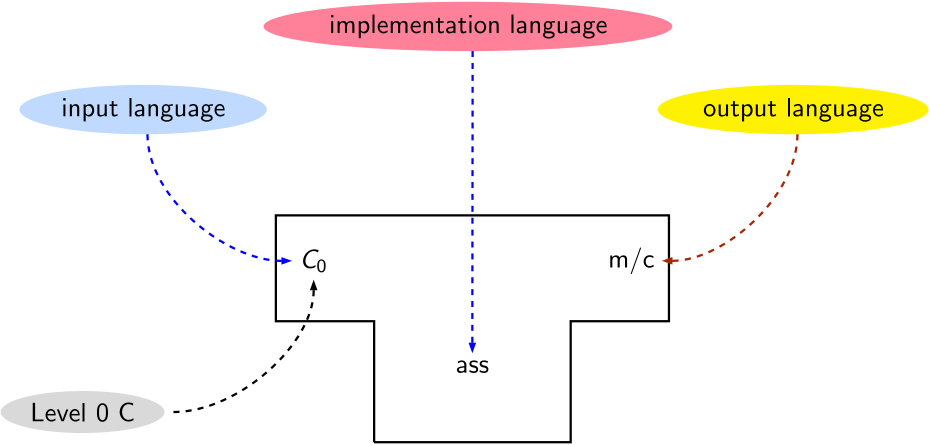

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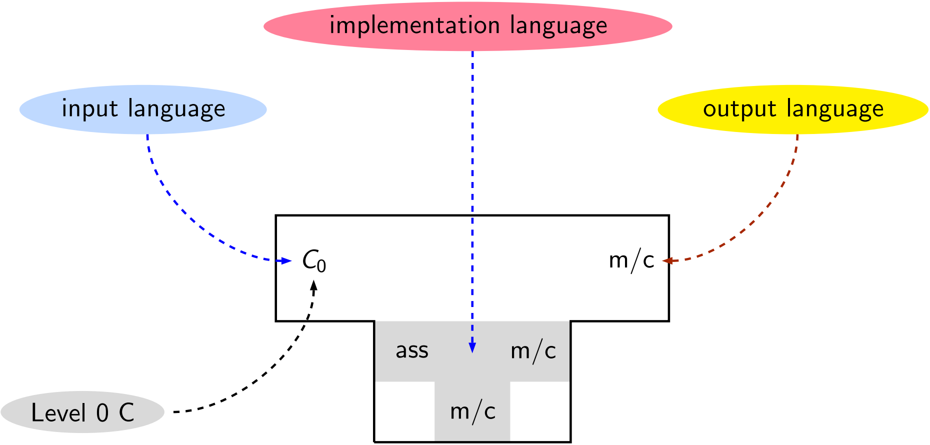

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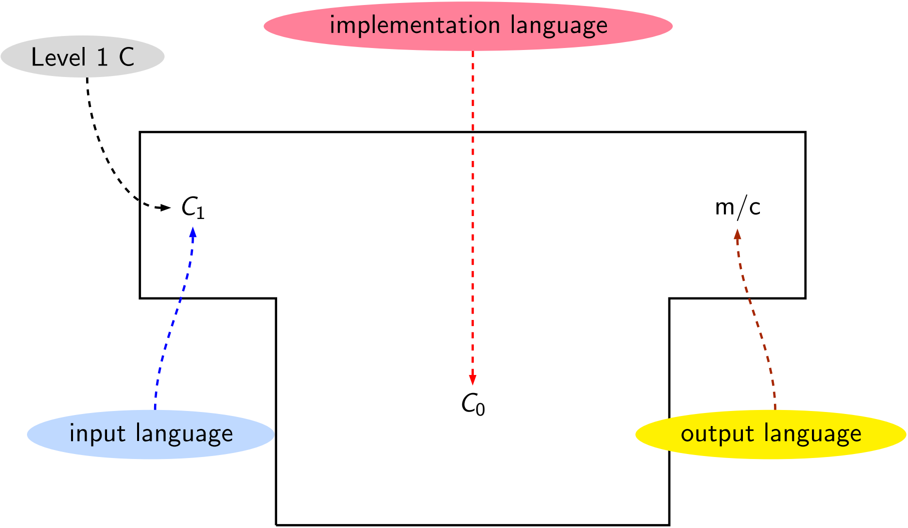

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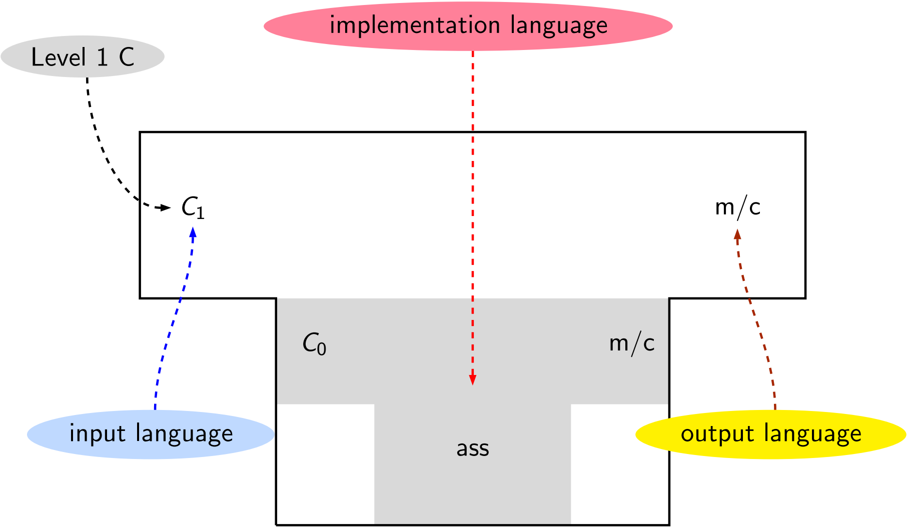

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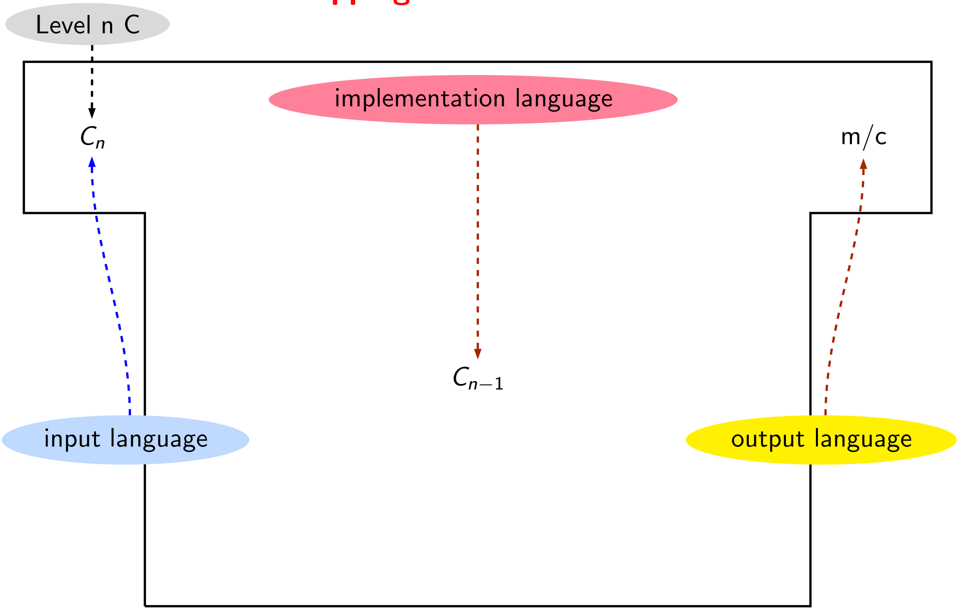

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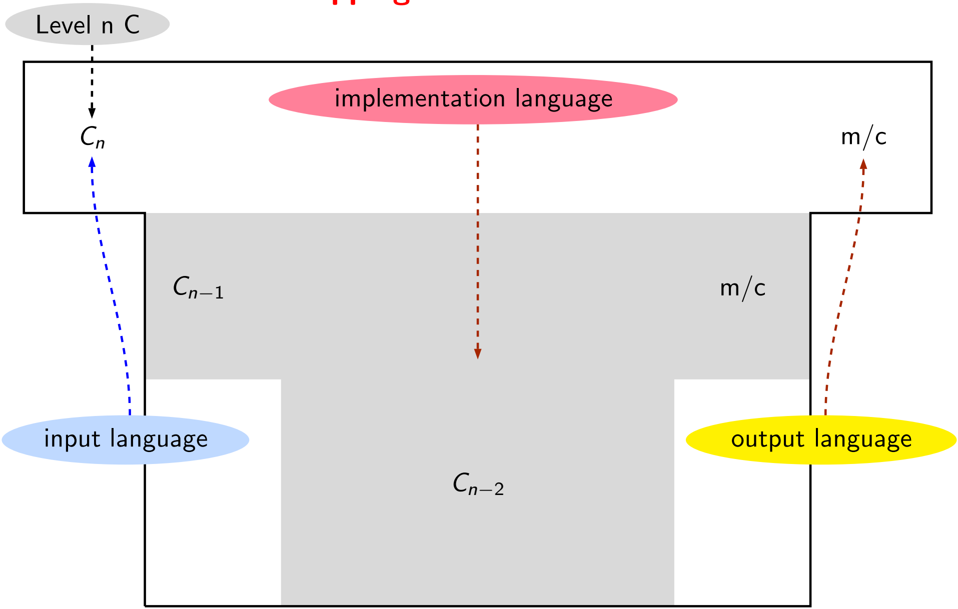

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Compiling-Challenges

Bootstrapping: GCC View

- Language need not change, but the compiler may change

  Compiler is improved, bugs are fixed and newer versions are released

- To build a new version of a compiler given a built old version:
  - Stage 1: Build the new compiler using the old compiler
  - Stage 2: Build another new compiler using compiler from stage 1
  - Stage 3: Build another new compiler using compiler from stage 2

    Stage 2 and stage 3 builds must result in identical compilers

⇒ Building cross compilers stops after Stage 1!

The Beauty and Enormity of Compiling

- Bridging the rather large gap between high and low level languages
  - Creating several layers of abstractions with smaller gaps
  - A great example of divide and conquer or stepwise refinement
- Developing and maintaining a rather large code base of millions of lines

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- Exploiting advanced features of rich computer architectures
- Spanning both theory and practice (and everything in between) rather deeply
  Translating deep theory into general, efficient, and scalable, practice!

Modern Compilers Span Both Theory and Practice Deeply

Compiler design and implemetation translates deep theory into general, efficient, and scalable, practice!

- Uses principles and techniques from many areas in Computer Science
  - The design and implementation of a compiler is a great application of software engineering
  - Makes practical application of deep theory and algorithms and rich data structures
  - Uses rich features of computer architecture

Translating Deep Theory into Affordable Practice

- Theory and algorithms
  - Mathematical logic: type inference and checking
  - Lattice theory: static analysis
  - Linear algebra: dependence analysis and loop parallelization
  - Probability theory: hot path optimization
  - Greedy algorithms: register allocation
  - Heuristic search: instruction scheduling
  - Graph algorithms: register allocation
  - Dynamic programming: instruction selection
  - Optimization techniques: instruction scheduling
  - Finite automata: lexical analysis
  - Pushdown automata: parsing
  - Fixed point algorithms: data-flow analysis

Credits: Adapted from the slides of Prof. Y. N. Srikant, IISc Bangalore

Translating Deep Theory into Affordable Practice

- Data structures
  - Sparse representations: scanner and parser tables
  - Stacks, lists, and arrays: Symbols tables
  - Trees: abstract syntax trees, expression trees
  - Graphs: control flow graphs, call graphs, data dependence graphs,
  - DAGs: Expression DAG
  - Representing machine details such as instruction sets, registers, etc.

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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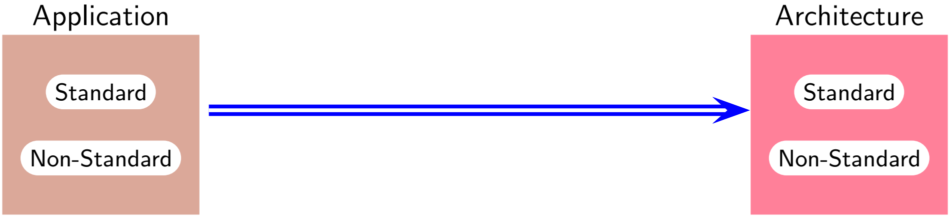
  - Parsing, Data flow analysis, Parallism Discovery, Heap Analysis

Compilation for Embedded Processors



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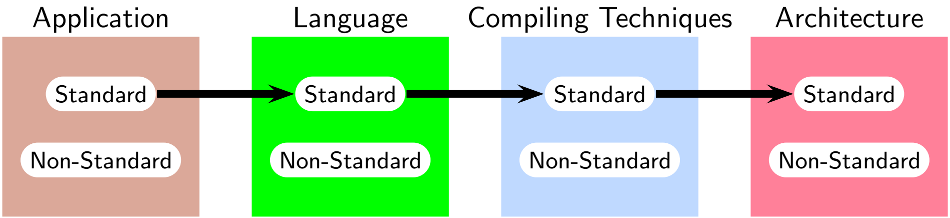

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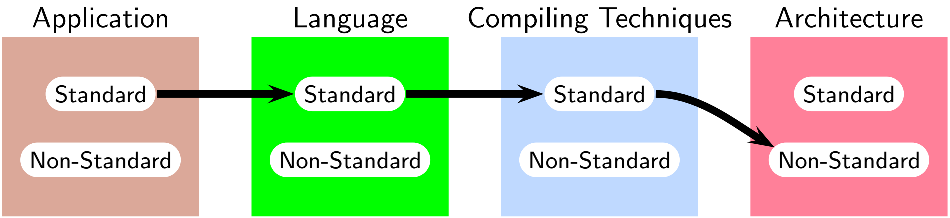

- Special addressing modes (viz. on-chip addressable memory)
- Use of predicated instructions

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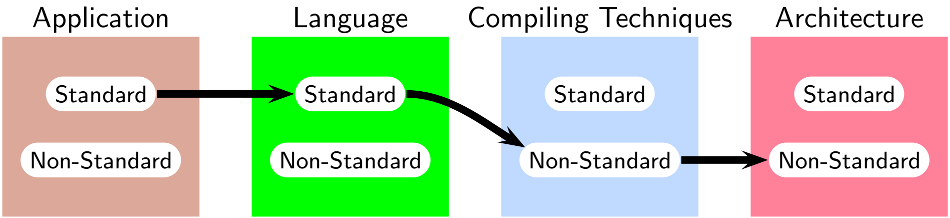
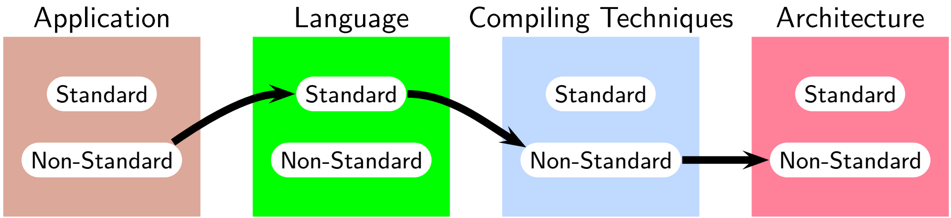
Compilation for Embedded Processors



- SIMD operations, Extracting ILP for VLIW
- Offset assignment, Array reference allocation

Compilation for Embedded Processors



- MACs, Special loop instructions

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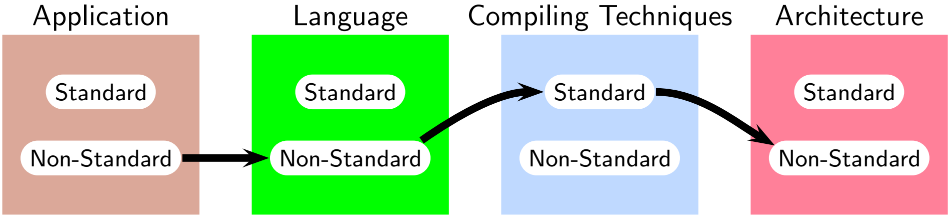
Compilation for Embedded Processors



- Setting arithmetic modes, circular addressing, special loop instructions

Modern Challenges: Design issues

- The IR interface

  What to export? What to hide?

  The most challenging component to design and implement in a compiler is the IR handler

- Retargetability

  Extending to the new version of a processor?

  Extending to a new processor?

Modern Challenges: Improving Performance of Programs

- Scaling analysis to large programs without losing precision
  - Interprocedural analysis
  - Pointer analysis

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  - Using run time information for improving optimizations in the next compilation
    (Profile guided optimization aka feedback driven optimization)

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  (Profile guided optimization aka feedback driven optimization)

> *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

- Inventing more effective optimizations

Modern Challenges: Language Issues

- How to efficiently compile
  - Dynamic features such as closures, higher order functions (eg. eval in Javascript)
  - Exceptions
- What guarantees to give in the presence of undefined behaviour
  - Memory accesses such as array access out of bound
- Designing analyses for features supporting parallellism
  - Doall, Async, Threads, Syncronization, Fork/Join, Lock/Unlock, Mutex, Semaphores
  - Some feaures enable parallelism in a sequential language whereas some enforce sequentiality on essentially parallel execution
- Designing analyses for extracting parallelism

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

The crux of the matter

- Hardware is parallel, (conventional) software is sequential
  - Software view of memory model: Strong consistency
    Every execution with the same input should give the same result
  - Hardware view of memory model: Sequential consistency
    Result should coincide with some interleaving of threads
    (Parallelism at the granularity of instructions in threads)
  - Modern architectures gives weak consistency
    (Parallelism at the granularity of pipeline units of instructions, e.g., load/store buffering)
- Software view is stable, hardware is disruptive

Architecture Feature Influencing Programming Language

A concurrent program

Initially $X = Y = 0$

Thread 1		Thread 2
$a = X$	$\parallel$	$b = Y$
$Y = 1$		$\text{if}(b)\ X = 1$

- Variables a and b are thread-local variables
- Variables X and Y are shared global variables

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Sequential Consistency preserves program order

$a = X$	$b = Y$	$b = Y$	$b = Y$	$a = X$	$a = X$
$Y = 1$	$b?\ X=1$	$a = X$	$a = X$	$b = Y$	$b = Y$
$b = Y$	$a = X$	$b?\ X=1$	$Y = 1$	$b?\ X=1$	$Y = 1$
$b?\ X=1$	$Y = 1$	$Y = 1$	$b?\ X=1$	$Y = 1$	$b?\ X=1$
$a=0, b=1$	$a = b = 0$	$a = b = 0$	$a = b = 0$	$a = b = 0$	$a = b = 0$

Architecture Feature Influencing Programming Language

A concurrent program

To see the difference between sequential consistency and strict consistency, consider the following interleaving of two threads

$a = 0$
$a = 1$
print a
print a

- Strict consistency. Result of writes are available instantaneously

  Both prints of a must read the value 1

  $\Rightarrow$ Only one result is possible: 1, 1

- Sequential consistency. Result of writes may be available with a delay

  The first print of a may read 0

  $\Rightarrow$ Both 0, 1 and 1,1 are possible

Architecture Feature Influencing Programming Language

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Relaxed Memory Consistency allows violating program order

$Y = 1$
$b = Y$
$b?\ X = 1$
$a = X$
$a = b = 1$

- Order of assignments in the first thread can be interchanged
  No thread-local data dependence
- Supported by out-of-order execution in processors restricted to a local view of the threads
- Being pushed in C standard in spite of the fact that it is difficult to understand for a programmer

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IIT Bombay

Talk Title:
Compiling-Challenges

Architecture Feature Influencing Programming Language

A concurrent program

Initially $X = Y = 0$

$a = X$	$\|\|$	$b = Y$
$Y = 1$		if(b)

- Variables a and b are thread-local variables
- d global variables

Why is this useful?

Out of order execution offers more opportunities of keeping the pipeline full, thereby increasing the throughput

Relaxed m order

n be interchanged

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$b = Y$

$b?\ X = 1$

$a = X$

$a = b = 1$

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Modern Challenges: Providing Guarantees

- Correctness of optimizations
  - Hard even for machine independent optimizations
  - Verification of a production optimizing compiler is a pipe dream
    Requires proving the correctness of translation of ALL programs
  - Compiler validation is more realistic, and yet not achieved fully
    Allows proving the correctness of translation of A program
- Interference with Security
  - Optimizations disrupt memory view
    Correctness is defined in terms of useful states
    Clearing stack location by writing all zeros is dead code
  - Optimizations also disrupt timing estimates

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Compiler Verification

Formalize and verify the following diagram for every source program P

$$\begin{tikzcd} \mathbf{P} \arrow[r] \arrow[d] & \mathit{comp}(\mathbf{P}) \arrow[d] \\ \mathit{sMean}(\mathbf{P}) & \mathit{tMean}(\mathit{comp}(\mathbf{P})) \arrow[l, "\text{abstract}"'] \end{tikzcd}$$

comp represents the transformation performed by

- a compiler (harder problem), or
- a model of the compiler (easier)

  Is the model faithful?

Credits: Adapted from the slides of Prof. Amitabha Sanyal, IIT Bombay

Compiler Verification

Formalize and verify the following diagram for every source program P

$y = 5$
$x = y + 1$

```
li $t0, 5
sw $t0, 4($fp)
lw $t0, 4($fp)
addi $t0, 1
sw $t0, 8($fp)
```

$$
\begin{tikzcd}
\mathbf{P} \arrow[r] \arrow[d] & \mathit{comp}(\mathbf{P}) \arrow[d] \\
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$$

$y = 5$
$x = 6$

$M[4(\$fp)] = 5$
$M[8(\$fp)] = 6$

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Difficulties in Compiler Verification

- Complexity
  - Requires reasoning about actual compiler implementation.
  - Requires reasoning about the behaviour of the compiler for an infinite number of programs and their translations.
- Automation - unlikely
- Proof reuse?

Credits: Adapted from the slides of Prof. Amitabha Sanyal, IIT Bombay

Translation Validation

Formalize and verify the following diagram for a given source program P

$$
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Translation Validation

- Less complex
    - Involves reasoning about a given pair of programs
    - The compiler can be made to provide information to help verification.
- Automation - likely.

Credits: Adapted from the slides of Prof. Amitabha Sanyal, IIT Bombay

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

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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

The Wonder Element of FORTRAN

- Expressiveness Vs. Efficiency conflict
    - 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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  Backus argued so over three decades ago!

The Challenge Ahead

- 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

- The *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," Vijay D'Sivla et.al. (2015)
- Proceedings of the *History of Programming Languages* conferences: `https://dl.acm.org/conference/hopl/proceedings`

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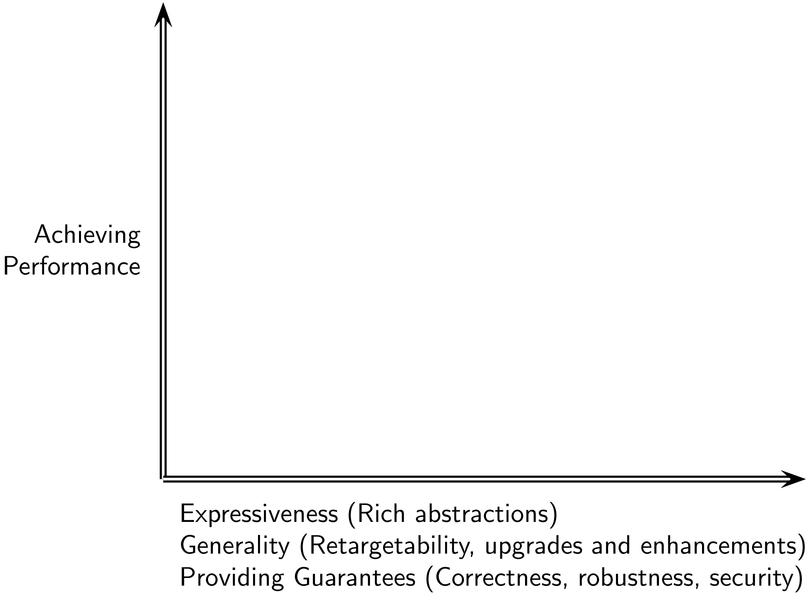
The Moral of the Story



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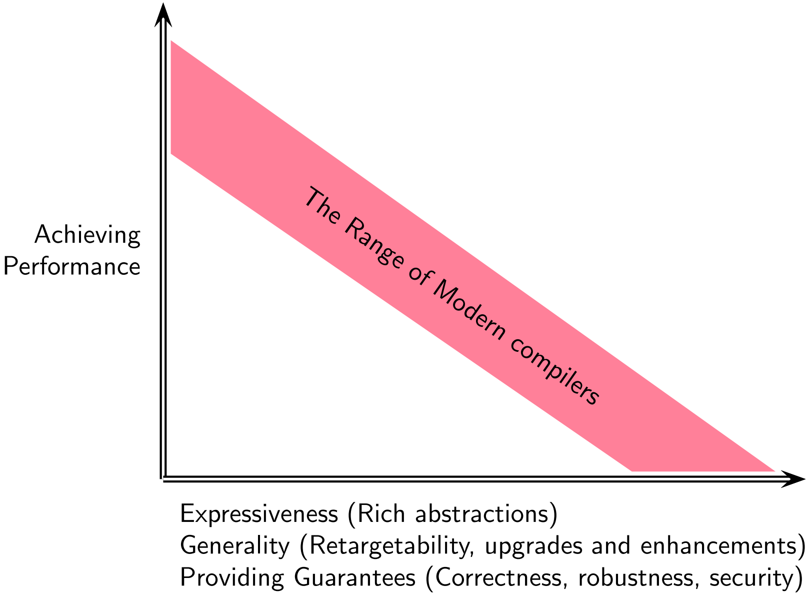
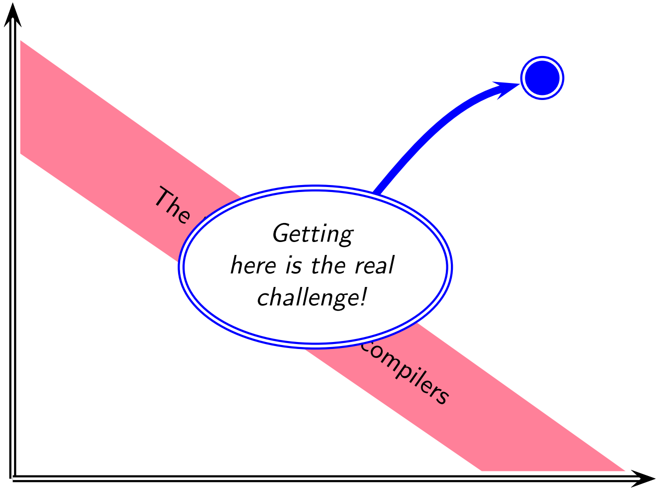


The Moral of the Story

Achieving Performance



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

Uday Khedker
IIT Bombay

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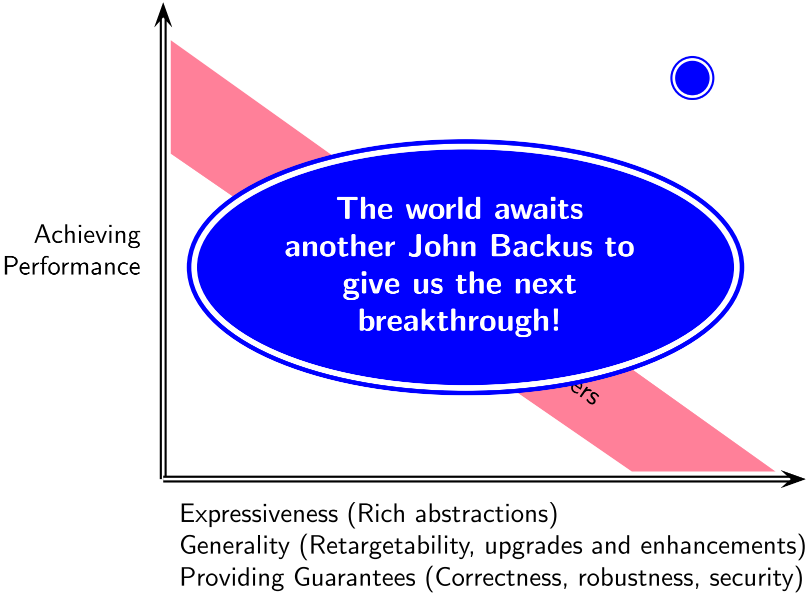

Last But Not the Least

Thank You!

Last But Not the Least

Thank You!

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