

# *An Overview of Compilation*

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**Topic:**

**Compilation Overview**

**Section:**

**Outline**

Introduction to  
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An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

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Expectation  
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of Programming  
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Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Outline



IIT Bombay  
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of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Outline

- Introduction
- Compilation phases
- Compilation models
- Modern challenges
- Incremental construction of compilers
- Course plan
- Expectation management



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**Topic:**

**Compilation Overview**

**Section:**

Outline

**Introduction to**  
**Compilation**

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

**Introduction to  
Compilation**

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Introduction to Compilation



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Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

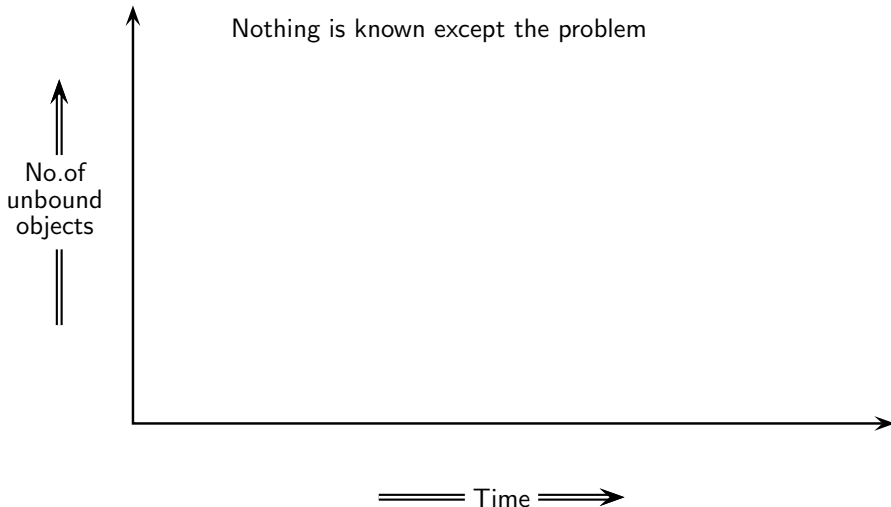
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

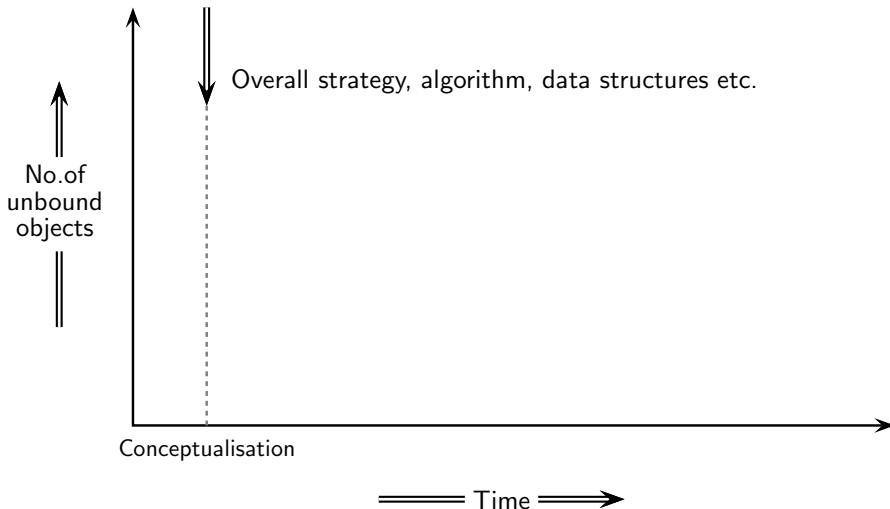
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Binding







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Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

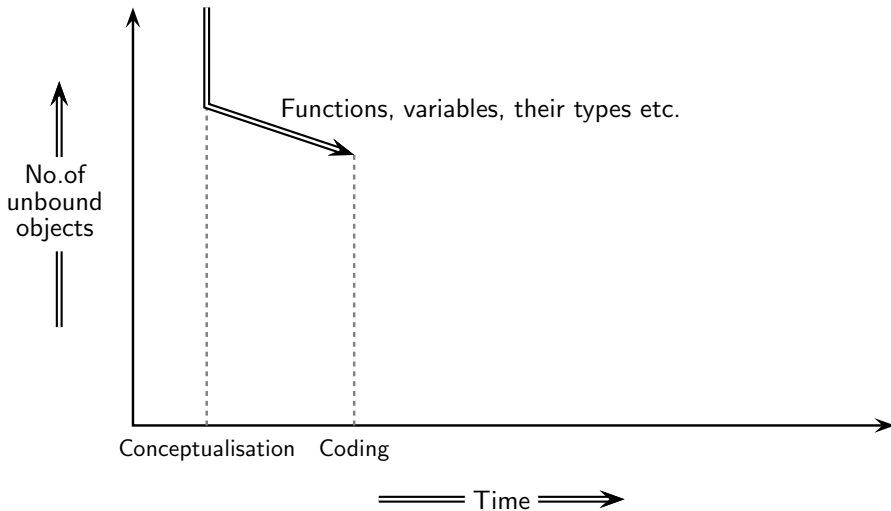
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Binding





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Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

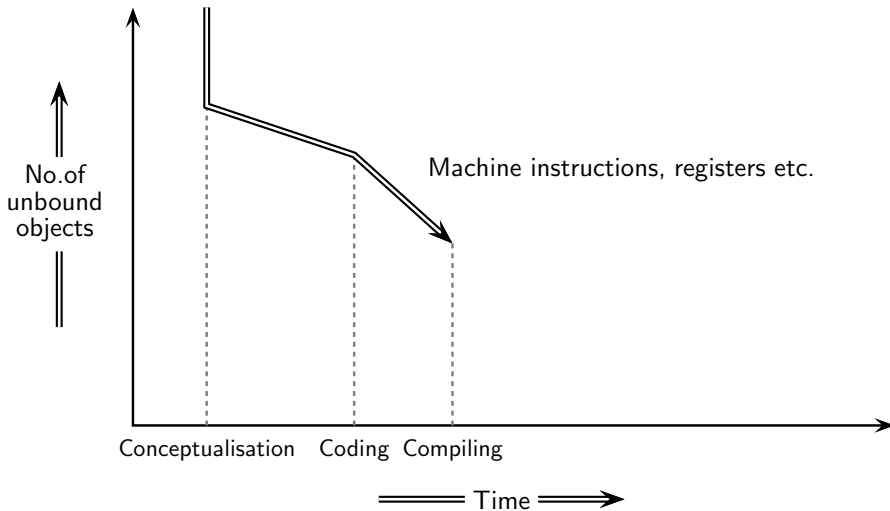
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Binding





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Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

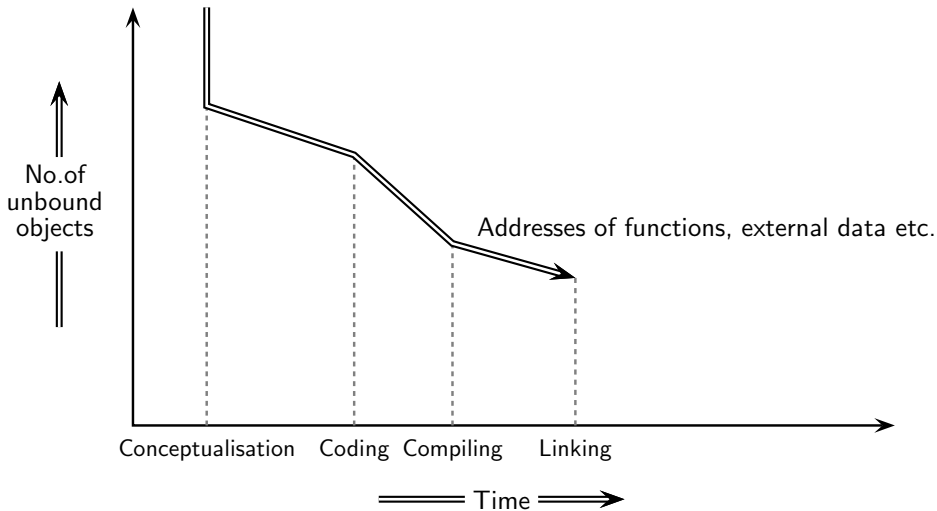
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Binding





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Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

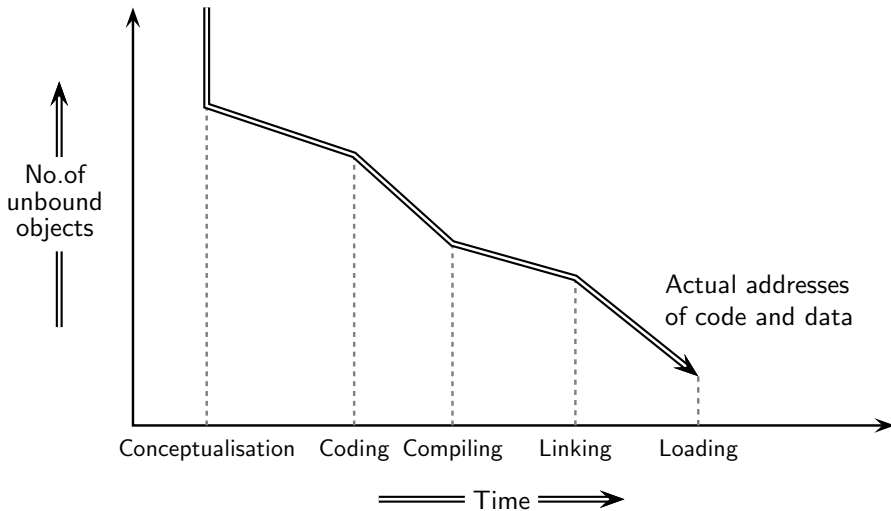
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Binding





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Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

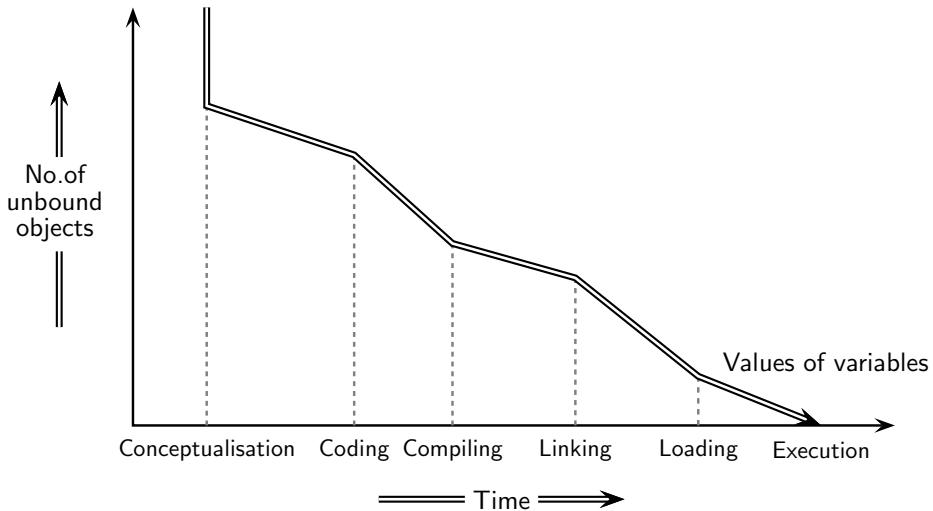
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Binding





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Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

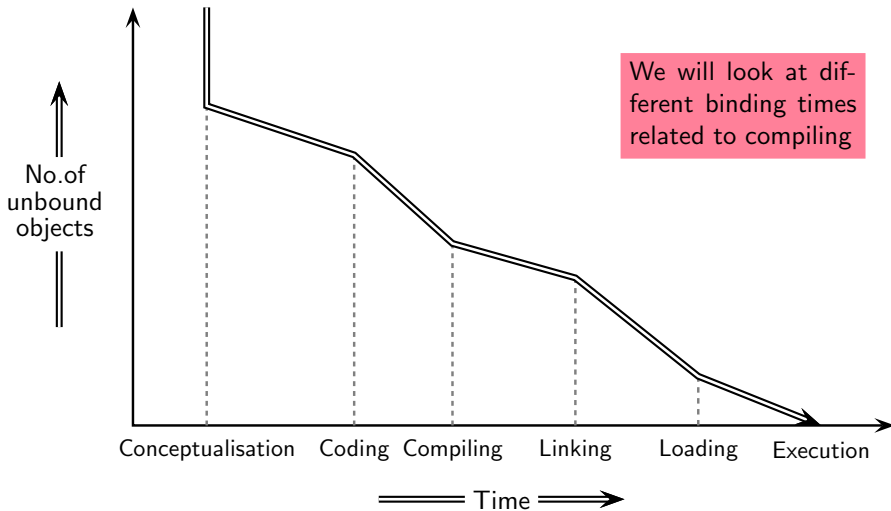
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Binding





# Implementation Mechanisms

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Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

Source Program



Translator



Target Program



Machine



# Implementation Mechanisms

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Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

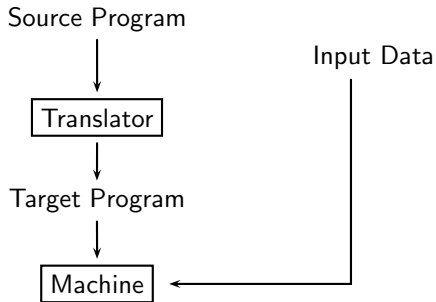
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management







# Implementation Mechanisms

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Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

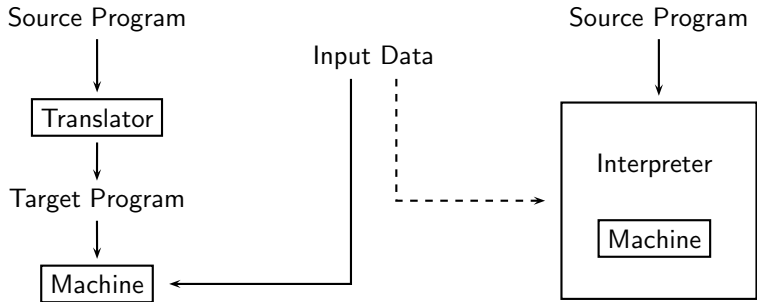
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Comparing the Implementation Mechanisms

Translation = Analysis + Synthesis

Interpretation = Analysis + Execution



# Comparing the Implementation Mechanisms

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of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

Translation = Analysis + Synthesis

Interpretation = Analysis + Execution

Implementation mechanism	Input	Output	Separate execution	Input for the input program
Translation	Program	Equivalent program	Required	Not required
Interpretation	Program	The result of the Program	Not required	Required



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Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Seeing the Difference Between Compilation and Interpretation

```
$ ./lp --help
```

```
Usage: lp [OPTION...]
```

-c	Compile the input into three address code and print it
-i	Interpret the input and print result
-, --help	Give this help list
--usage	Give a short usage message

```
$ ./lp -i
```

```
a = 10 + 20 * 30;
```

```
> a = 610
```

```
$ ./lp -c
```

```
a = 10 + 20 * 30;
```

The three address code generated for the input is

```
t0 = 20 * 30
```

```
t1 = 10 + t0
```

```
a = t1
```



# Implementation Mechanisms as “Bridges”

- “Gap” between the “levels” of program specification and execution

Program Specification

Machine

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Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

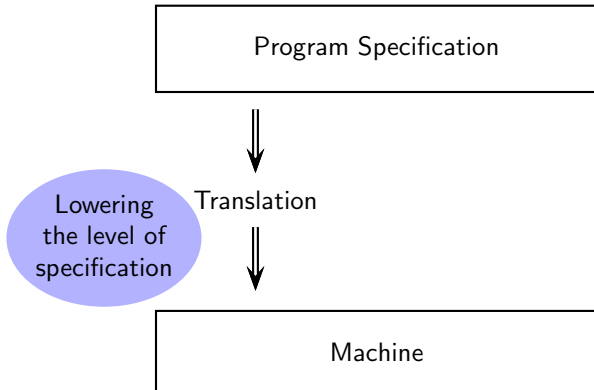
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Expectation  
Management



# Implementation Mechanisms as “Bridges”

- “Gap” between the “levels” of program specification and execution



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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

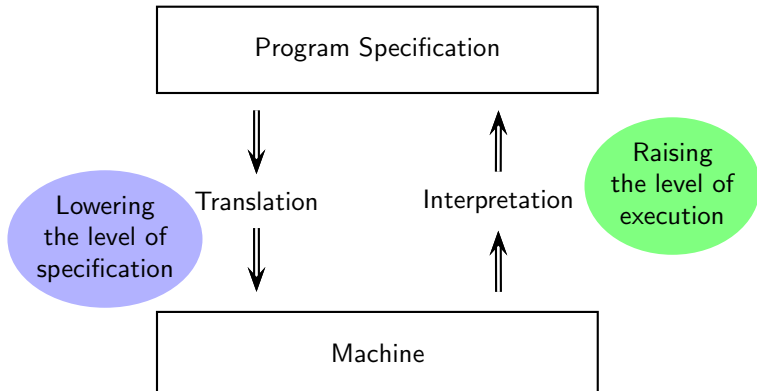
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Construction of  
Compilers

Course Plan

Expectation  
Management

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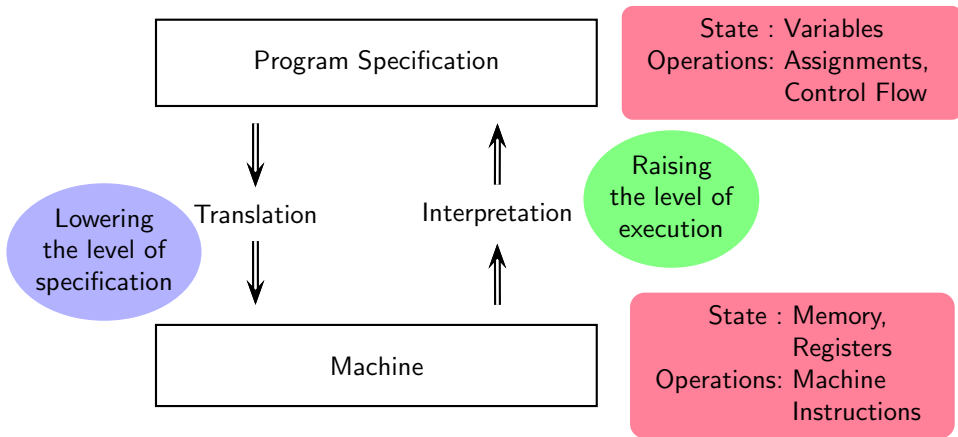
- “Gap” between the “levels” of program specification and execution





# Implementation Mechanisms as “Bridges”

- “Gap” between the “levels” of program specification and execution



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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# A Source Program in C++: High Level Abstraction

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Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models  
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

```
#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)

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Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

```

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)

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of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

```
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

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of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- 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



# High and Low Level Abstractions: Our View

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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

Input C statement

```
a = b<10?b:c+5;
```

Spim assembly equivalent (unoptimized)

```
lw    $v0, 4($fp) ;    v0 <- b           # Is b smaller
slti   $t1, $v0, 10 ;    t1 <- v0 < 10    # than 10?
xori   $t2, $t1, 1 ;    t2 <- !t1
bgtz   $t2, L0 ;        if t2 > 0 goto L0
lw     $t3, 4($fp) ;    t3 <- b           # YES
b      L1 ;            goto L1
L0: lw  $t4, 8($fp) ;L0: t4 <- c           # NO
      addi $t3, $t4, 5 ;    t3 <- t4 + 5    # NO
L1: sw  0($fp), $t3 ;L1: a <- t3
```



# High and Low Level Abstractions: Our View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

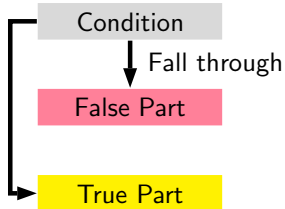
Course Plan

Expectation  
Management

Input C statement

```
a = b<10?b:c+5;
```

Conditional jump



Spim assembly equivalent (unoptimized)

```
lw    $v0, 4($fp) ;    v0 <- b           # Is b smaller
slti   $t1, $v0, 10 ;    t1 <- v0 < 10     # than 10?
xori   $t2, $t1, 1 ;    t2 <- !t1
bgtz   $t2, L0 ;        if t2 > 0 goto L0
lw     $t3, 4($fp) ;    t3 <- b           # YES
b      L1 ;             goto L1
L0: lw  $t4, 8($fp) ;L0: t4 <- c           # NO
      addi $t3, $t4, 5 ;    t3 <- t4 + 5    # NO
L1: sw  0($fp), $t3 ;L1: a <- t3
```



# High and Low Level Abstractions: Our View

NOT Condition

Input C statement

```
a = b<10?b:c+5;
```

True Part

False Part

Spim assembly equivalent (unoptimized)

```
lw    $v0, 4($fp) ;    v0 <- b           # Is b smaller
slti   $t1, $v0, 10 ;    t1 <- v0 < 10     # than 10?
xori   $t2, $t1, 1 ;    t2 <- !t1
bgtz   $t2, L0 ;        if t2 > 0 goto L0
lw     $t3, 4($fp) ;    t3 <- b           # YES
b      L1 ;            goto L1
L0: lw  $t4, 8($fp) ;L0: t4 <- c           # NO
      addi $t3, $t4, 5 ;    t3 <- t4 + 5    # NO
L1: sw  0($fp), $t3 ;L1: a <- t3
```

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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# High and Low Level Abstractions: Our View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

Input C statement

```
a = b<10?b:c+5;
```

Conditional jump

NOT Condition

Fall through

True Part

False Part

Spim assembly equivalent (unoptimized)

```

    lw    $v0, 4($fp) ;    v0 <- b           # Is b smaller
    slti   $t1, $v0, 10 ;    t1 <- v0 < 10     # than 10?
    xori   $t2, $t1, 1 ;    t2 <- !t1
    bgtz   $t2, L0 ;        if t2 > 0 goto L0
    lw     $t3, 4($fp) ;    t3 <- b           # YES
    b      L1 ;            goto L1
L0: lw     $t4, 8($fp) ;L0: t4 <- c           # NO
    addi   $t3, $t4, 5 ;    t3 <- t4 + 5      # NO
L1: sw     0($fp), $t3 ;L1: a <- t3

```





# Language Implementation Models

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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

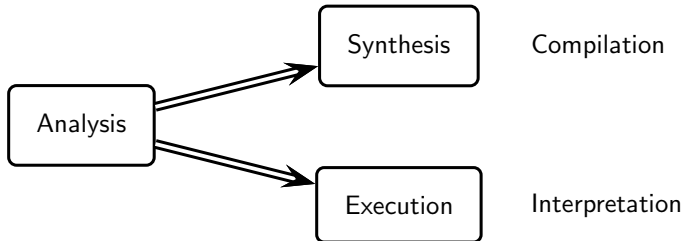
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Language Processor Models

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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

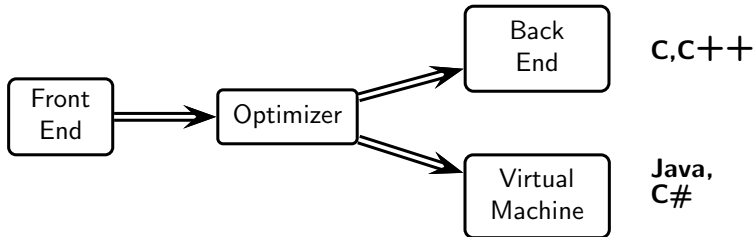
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Why Do We Need Compilers and Interpreters, Both?

$t$ : Time

$A$ : Analysis,  $O$ : Optimization,  $S$ : Synthesis,  $E$ : Execution,  $B$ : Bookkeeping

$p$ : Program,  $c$ : Compiler usage,  $i$ : Interpreter usage,  $j$ : Number of executions

$$t_c(p, j) = t_c^A(p) + t_c^O(p) + t_c^S(p) + \left( t_c^E(p) \times j \right)$$

$$t_i(p, j) = \left( t_i^A(p) + t_i^B(p) + t_i^E(p) \right) \times j$$

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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interpretation  
overheads

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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interpretation  
overheads

In general

- For large values of  $j$ ,  $t_c(p, j) \ll t_i(p, j)$

Overheads of compilation are amortized over multiple executions

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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interpretation  
overheads

In general

- For large values of  $j$ ,  $t_c(p, j) \ll t_i(p, j)$

Overheads of compilation are amortized over multiple executions

- For small values of  $j$ ,  $t_c(p, j) \gg t_i(p, j)$

Overheads of interpretations are meaningful for infrequently executed jobs

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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compilation  
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interpretation  
overheads

In general

- For large values of  $j$ ,  $t_c(p, j) \ll t_i(p, j)$   
Overheads of compilation are amortized over multiple executions
- For small values of  $j$ ,  $t_c(p, j) \gg t_i(p, j)$   
Overheads of interpretations are meaningful for infrequently executed jobs
- For any value of  $j > 0$ ,  $(t_c^E(p) \times j) \ll t_i(p, j)$   
Overheads of compilation are meaningful for jobs with large execution times

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Reusability of Language Processor Modules

## Front Ends

Language 1

Language 2

Language  $n$

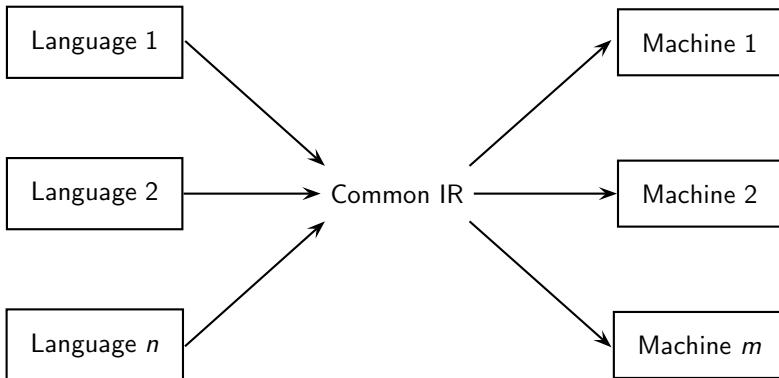
Common IR

## Back Ends/Virtual Machines

Machine 1

Machine 2

Machine  $m$



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of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Reusability of Language Processor Modules

## Front Ends

Language 1

Language 2

Language  $n$

Common IR

## Back Ends/Virtual Machines

Machine 1

Machine 2

Machine  $m$

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

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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



**IIT Bombay**  
**cs302: Implementation**  
**of Programming**  
**Languages**

**Topic:**

**Compilation Overview**

**Section:**

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# An Overview of Compilation Phases



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Structure of a Simple Compiler

Source Program



Assembly  
Program



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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

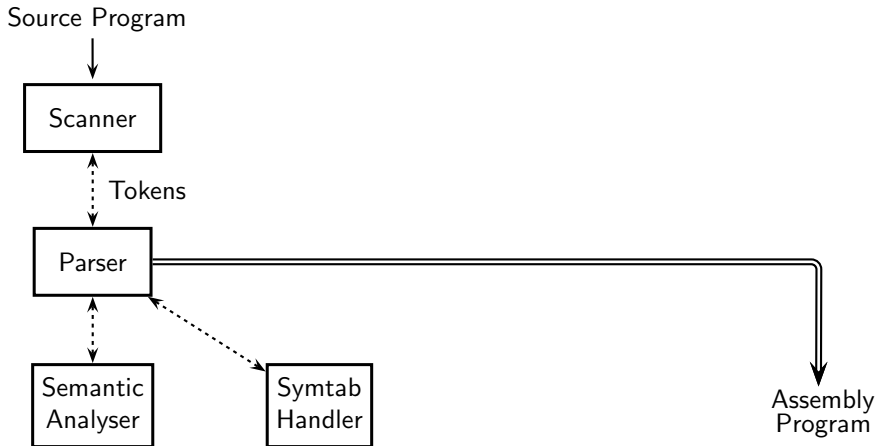
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Structure of a Simple Compiler





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

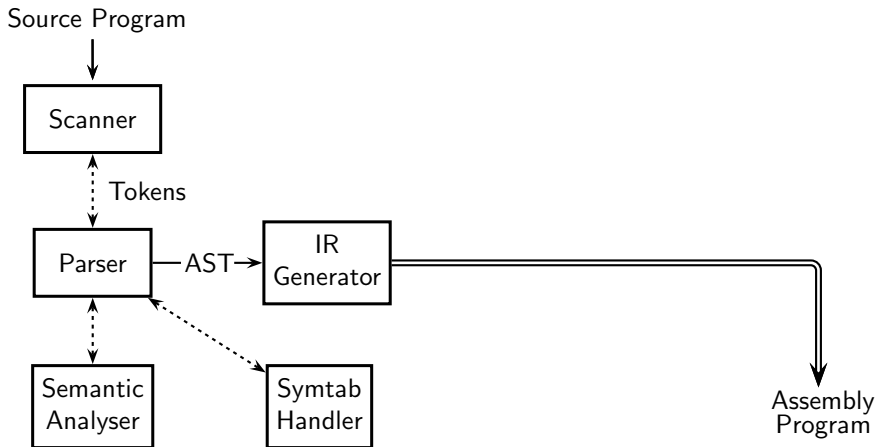
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Structure of a Simple Compiler





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

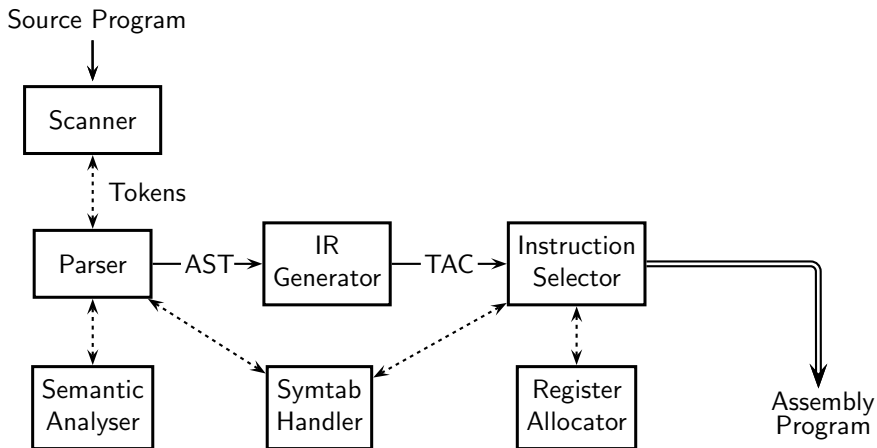
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Structure of a Simple Compiler





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

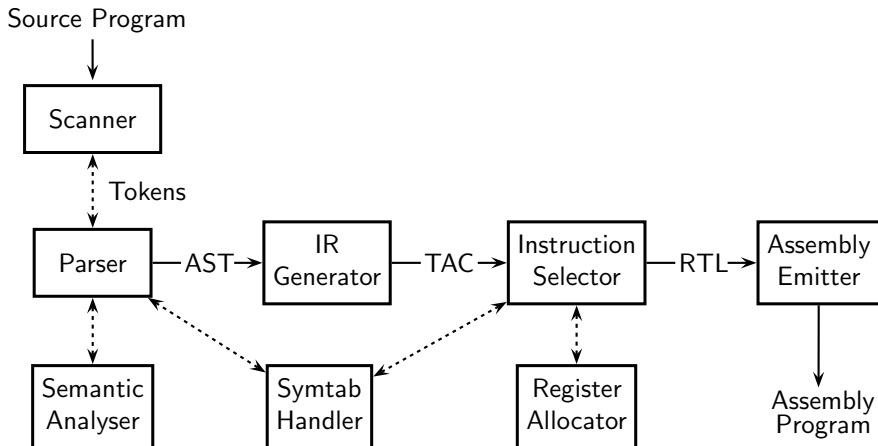
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Structure of a Simple Compiler







# Translation Sequence in Our Compiler: Scanning and Parsing

Input

```
a = b<10 ? b : c+5;
```

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

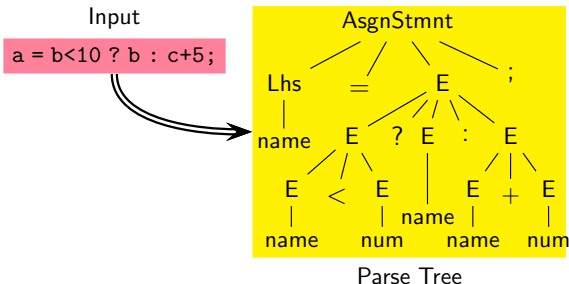
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Scanning and Parsing



How the input is actually stored in the memory

`a _ = _ b _ < _ 10 _ ? _ b _ : _ c _ + _ 5 _ ; _`

How we want to see it

`[a]_[=]_[b]_[<]_[10]_[?]_[b]_[:]_[c]_[+]_[5]_[;]_[_]`

Issues:

- Grammar rules, terminals, non-terminals
- Order of application of grammar rules  
eg. is it `(a = b < 10 ?)` followed by `(b : c)`?
- Values of terminal symbols  
eg. string "10" vs. integer number 10.



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

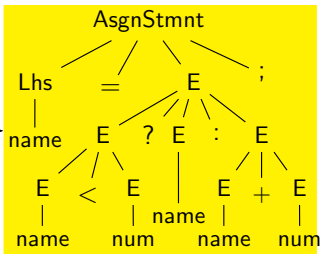
Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Semantic Analysis

Input

`a = b < 10 ? b : c + 5 ;`



Parse Tree



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cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

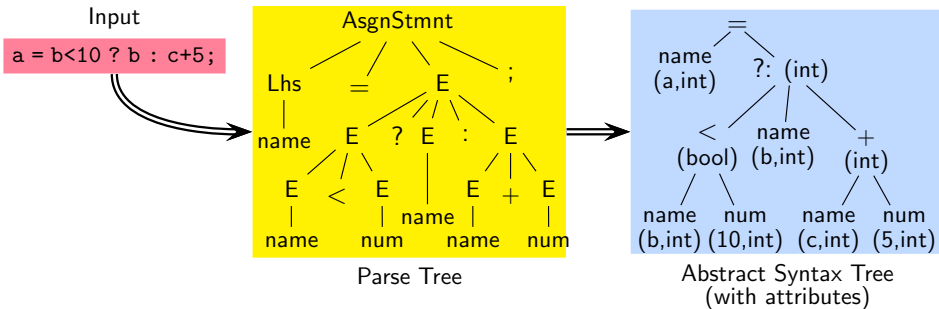
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Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Semantic Analysis



## Issues:

- Symbol tables  
Have variables been declared? What are their types?  
What is their scope?
- Type consistency of operators and operands  
The result of computing  $b < 10?$  is bool and not int



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

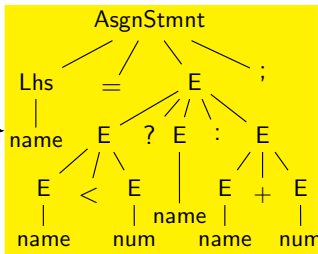
Course Plan

Expectation  
Management

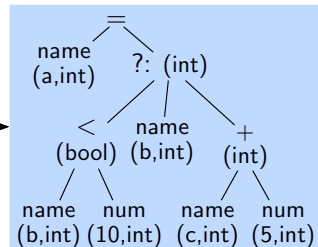
# Translation Sequence in Our Compiler: IR Generation

Input

`a = b < 10 ? b : c + 5;`



Parse Tree



Abstract Syntax Tree  
(with attributes)



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cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

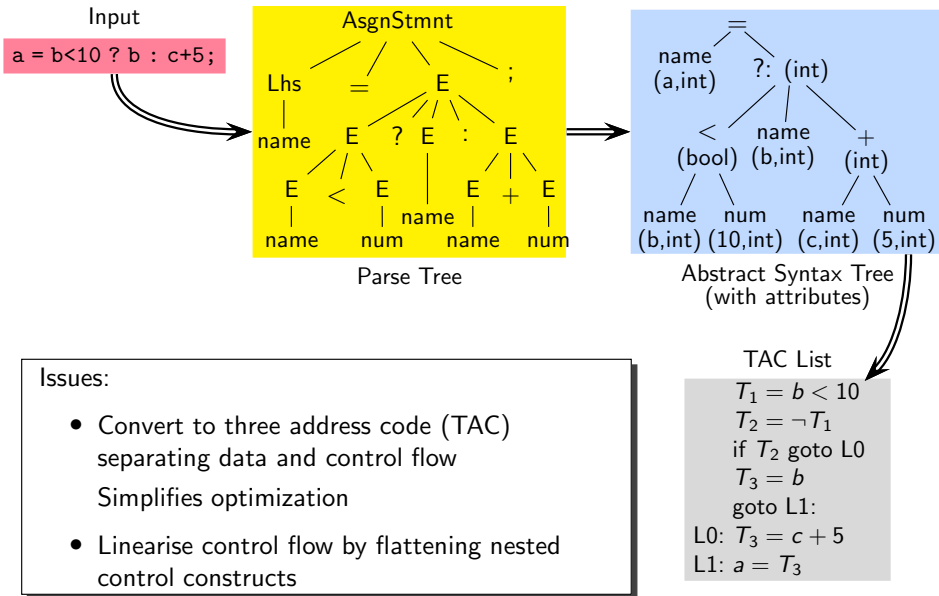
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: IR Generation







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

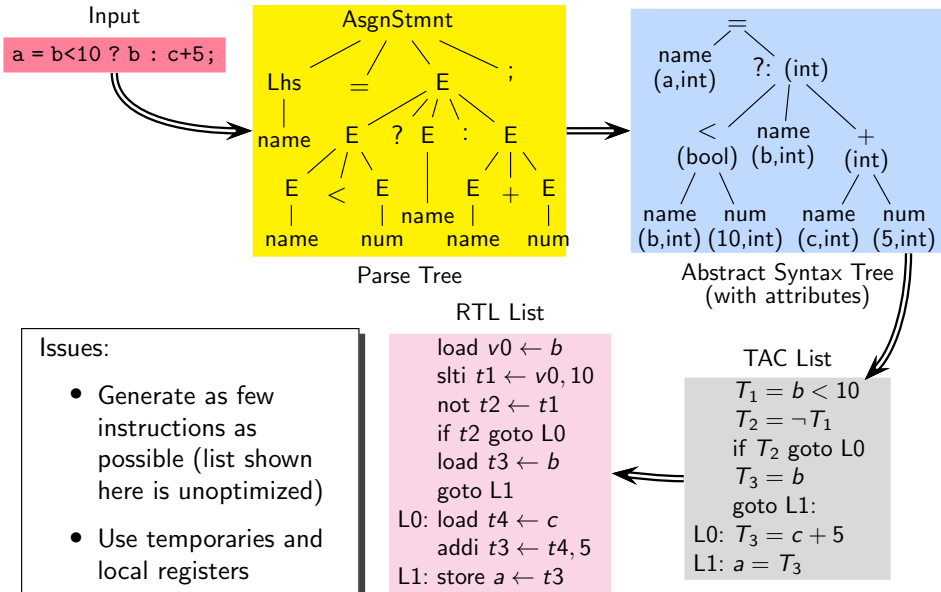
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Instruction Selection







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

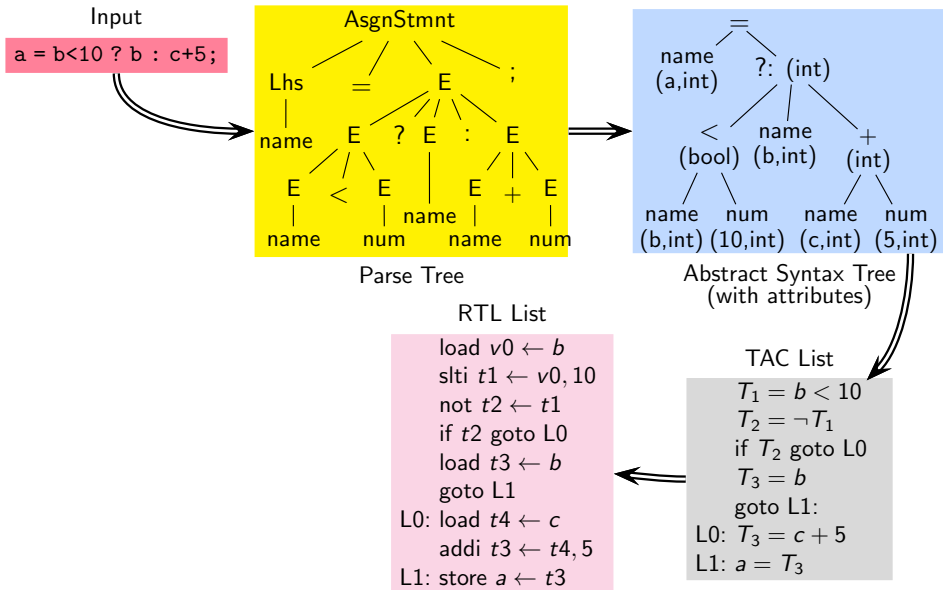
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Emitting Instructions





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

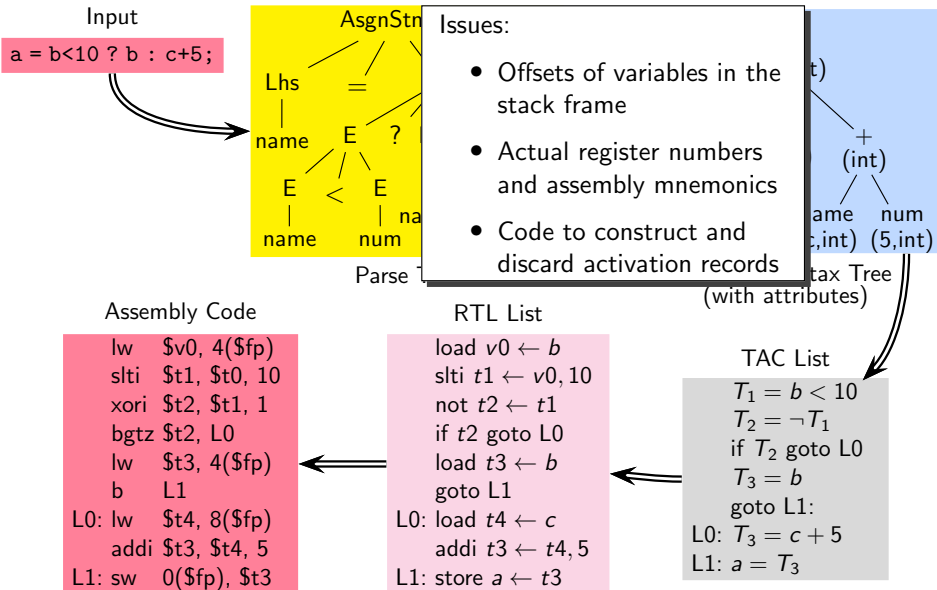
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Emitting Instructions





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

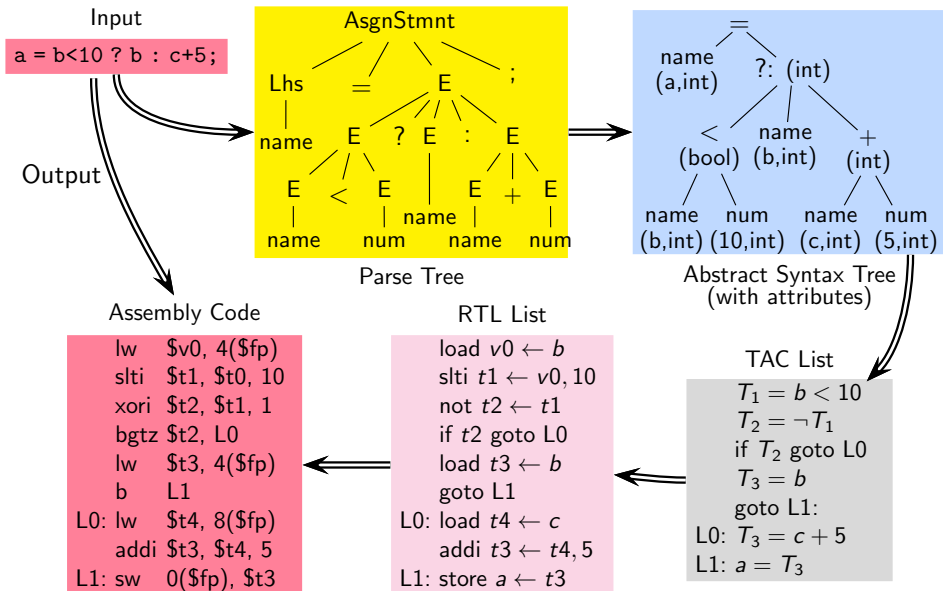
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Sequence in Our Compiler: Emitting Instructions





# Observations

- A compiler bridges the gap between source program and target program

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Observations

- A compiler bridges the gap between source program and target program
- Compilation involves gradual lowering of levels of the IR of an input program

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Observations

- A compiler bridges the gap between source program and target program
- Compilation involves gradual lowering of levels of the IR of an input program
- The design of IRs is the most critical part of a compiler design
  - How many IRs should we have?
  - What are the details that each IR captures?

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Observations

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- A compiler bridges the gap between source program and target program
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- The design of IRs is the most critical part of a compiler design
  - How many IRs should we have?
  - What are the details that each IR captures?
- Practical compilers are desired to be retargetable
  - ⇒ Back ends should be generated from specifications

# Why Is Compiler Construction a Relevant Course?



Even though very few people write compilers . . .

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

Even though very few people write compilers . . .

- Translation and interpretation are fundamental CS at a conceptual level
  - Stepwise refinement Vs. look up
  - Analytics Vs. Transactional software

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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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- Computer Science is all about building layers of abstractions and bridging the gaps between successive layers

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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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  - Knowing compilers internals makes a person a much better programmer
- Writing programs whose data is programs

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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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- 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 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



# Where Can I Use the Lessons Learnt in Compiler Design?

- Compilers for all languages exist, so what can I do with the technology?

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Where Can I Use the Lessons Learnt in Compiler Design?

- Compilers for all languages exist, so what can I do with the technology?
- Compiler techniques and tools have many applications
  - Parsers for HTML in web browser
  - Interpreters for javascript/flash
  - Machine code generation for high level languages
  - Software testing
  - Program optimization
  - Detection of malicious code
  - Design of new computer architectures
  - Hardware-software codesign!
  - Hardware synthesis: VHDL to RTL translation
  - Compiled simulation to simulate designs written in VHDL

Credits: Adapted from the slides of Prof. Y. N. Srikant for NPTEL course on compilers

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# 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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

**An Overview of  
Compilation Phases**

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# 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
- Writing programs that read programs and write programs maintaining the semantics





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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# 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
- Writing programs that read programs and write programs maintaining the semantics
- Extensive use of tools to generate modules from declarative specifications  
“Higher” level than HLLs



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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- Handling every possible programs from an infinite set of possible programs



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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- Exploiting advanced features of rich computer architectures



# The Beauty and Enormity of Compiling

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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“Higher” level than HLLs
- Handling every possible programs from an infinite set of possible programs
- 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 implementation 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

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translating Deep Theory into Affordable Practice



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- 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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- 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.



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**cs302: Implementation**  
**of Programming**  
**Languages**

**Topic:**

**Compilation Overview**

**Section:**

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

**Compilation Models**

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

**Compilation Models**

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Compilation Models



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

**Compilation Models**

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Compilation Models

*Aho Ullman  
Model*

*Davidson Fraser  
Model*

Excluded for cs302 of 2023-24



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

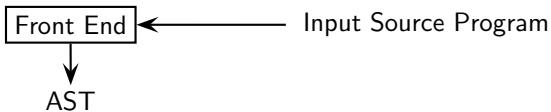
Course Plan

Expectation  
Management

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Model*

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Excluded for cs302 of 2023-24



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

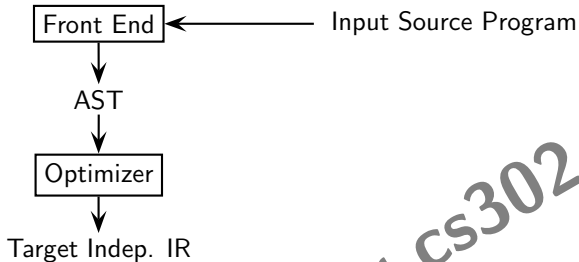
Course Plan

Expectation  
Management

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Model*

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Excluded for cs302 of 2023-24



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

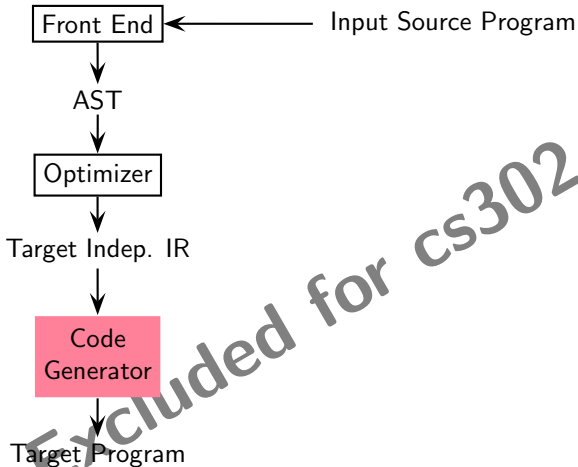
Course Plan

Expectation  
Management

# Compilation Models

*Aho Ullman  
Model*

*Davidson Fraser  
Model*





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

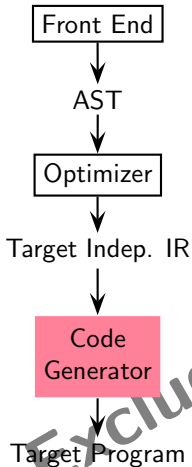
Incremental  
Construction of  
Compilers

Course Plan

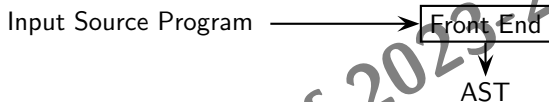
Expectation  
Management

## Compilation Models

*Aho Ullman  
Model*



*Davidson Fraser  
Model*





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

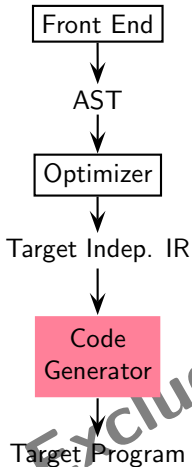
Incremental  
Construction of  
Compilers

Course Plan

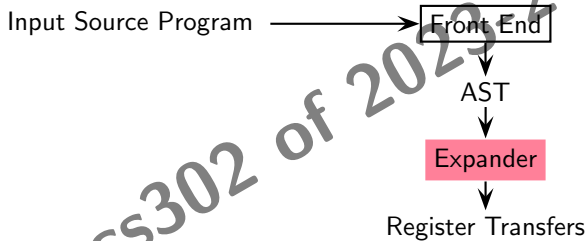
Expectation  
Management

## Compilation Models

### Aho Ullman Model



### Davidson Fraser Model





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

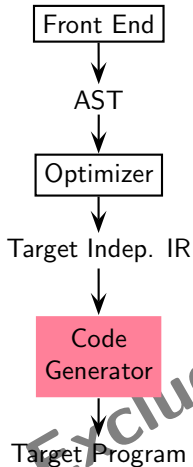
Incremental  
Construction of  
Compilers

Course Plan

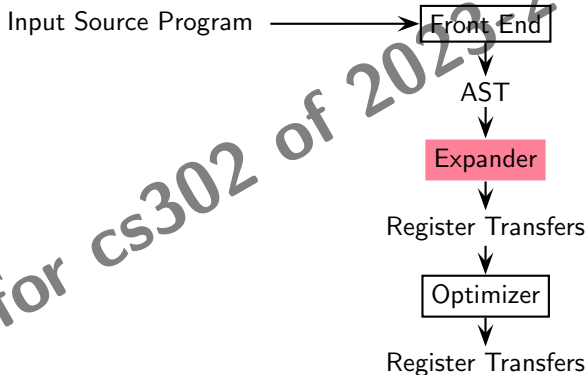
Expectation  
Management

## Compilation Models

### Aho Ullman Model



### Davidson Fraser Model







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

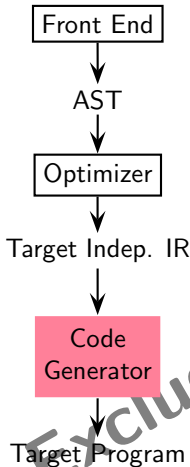
Incremental  
Construction of  
Compilers

Course Plan

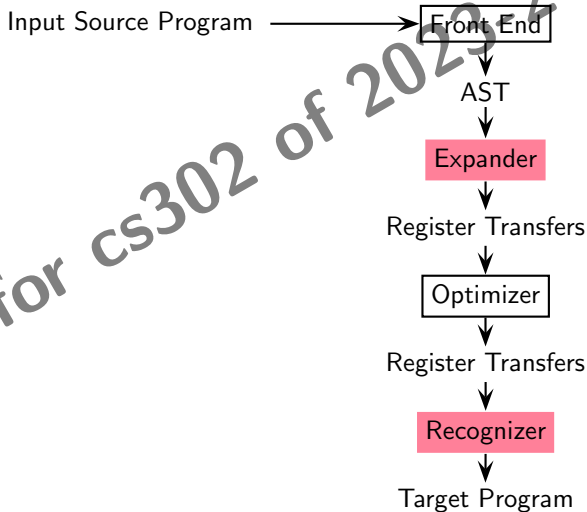
Expectation  
Management

# Compilation Models

## Aho Ullman Model



## Davidson Fraser Model





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

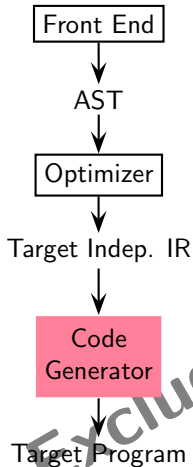
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Compilation Models

## Aho Ullman Model



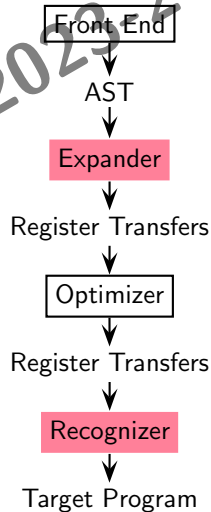
Aho Ullman: Instruction selection

- 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





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

**Compilation Models**

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Typical Front Ends

Parser



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

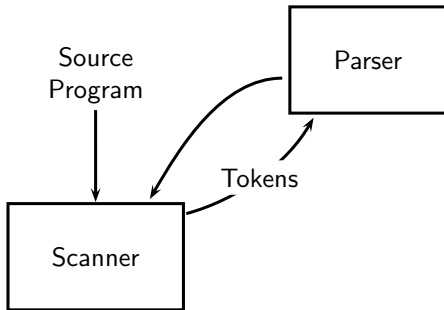
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Typical Front Ends





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

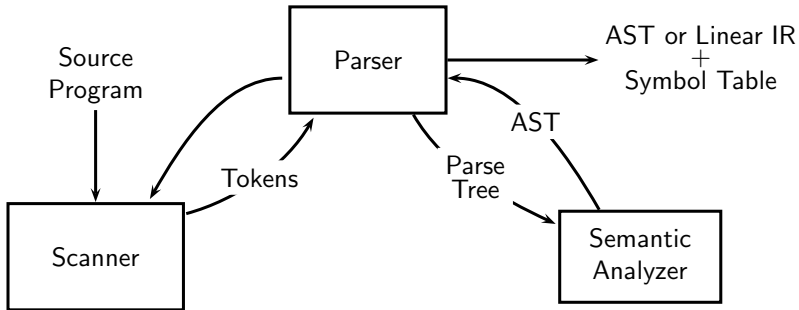
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Typical Front Ends





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

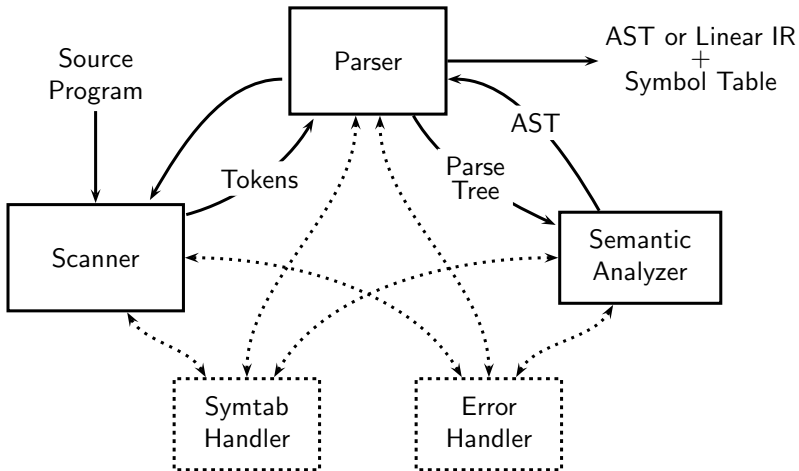
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Typical Front Ends





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

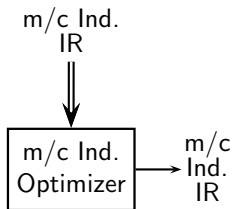
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Typical Back Ends



- Compile time evaluations
- Eliminating redundant computations



## Typical Back Ends

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

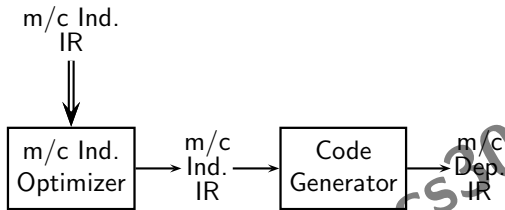
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



- Compile time evaluations
  - Instruction Selection
  - Local Reg Allocation
- Eliminating redundant computations
  - Choice of Order of Evaluation





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

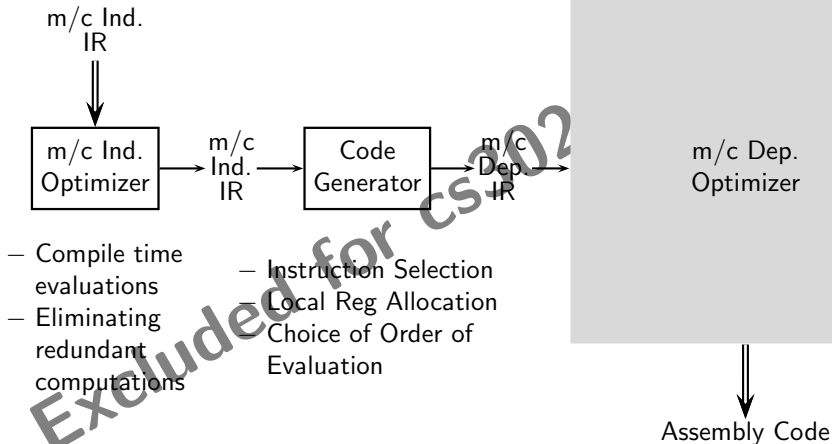
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Typical Back Ends





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

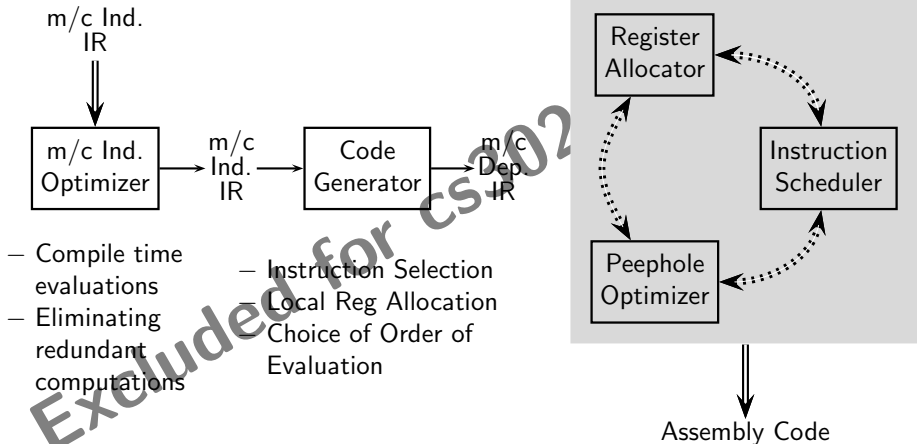
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Typical Back Ends





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

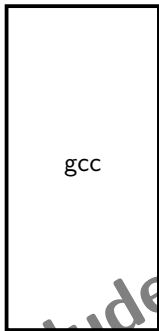
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The GNU Tool Chain for C

Source Program



Target Program

Excluded for cs302 of 2023-24



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

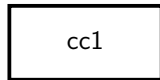
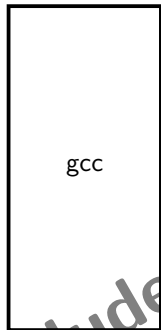
Incremental  
Construction of  
Compilers

Course Plan

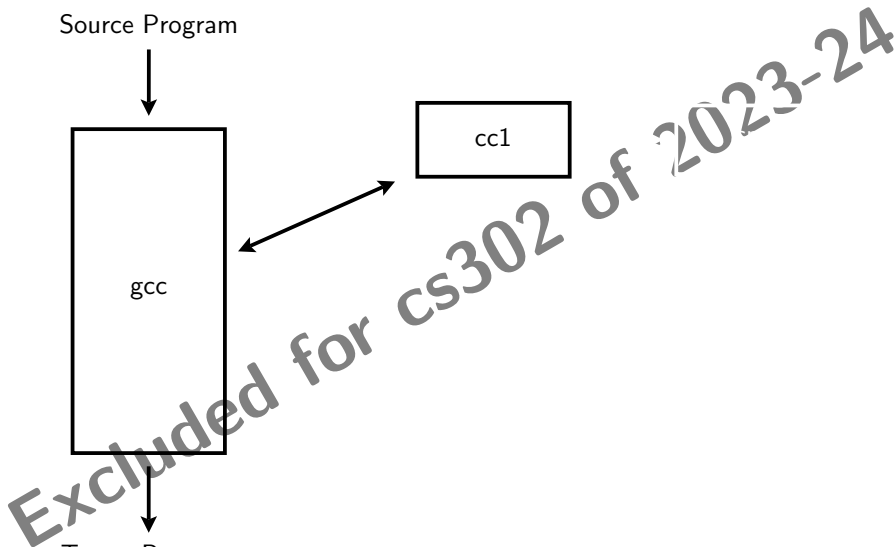
Expectation  
Management

# The GNU Tool Chain for C

Source Program



Target Program





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

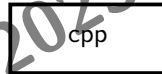
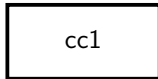
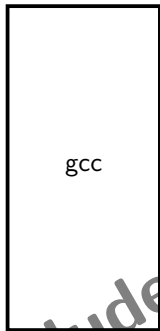
Incremental  
Construction of  
Compilers

Course Plan

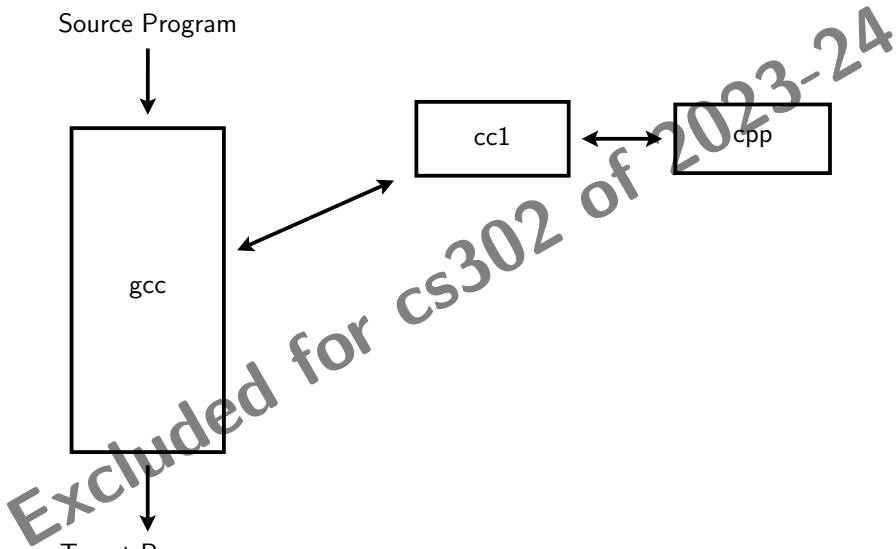
Expectation  
Management

## The GNU Tool Chain for C

Source Program



Target Program





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

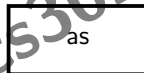
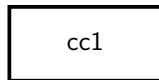
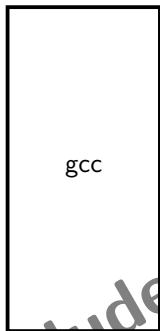
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The GNU Tool Chain for C

Source Program



Target Program



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

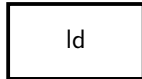
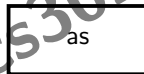
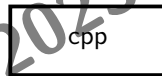
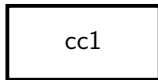
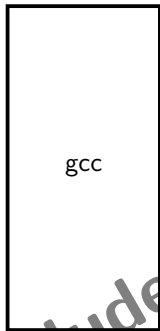
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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Source Program



Target Program



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

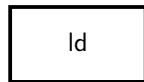
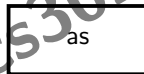
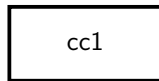
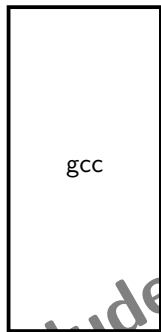
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The GNU Tool Chain for C

Source Program



glibc/newlib

Target Program





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The GNU Tool Chain for C

Source Program



gcc



Target Program

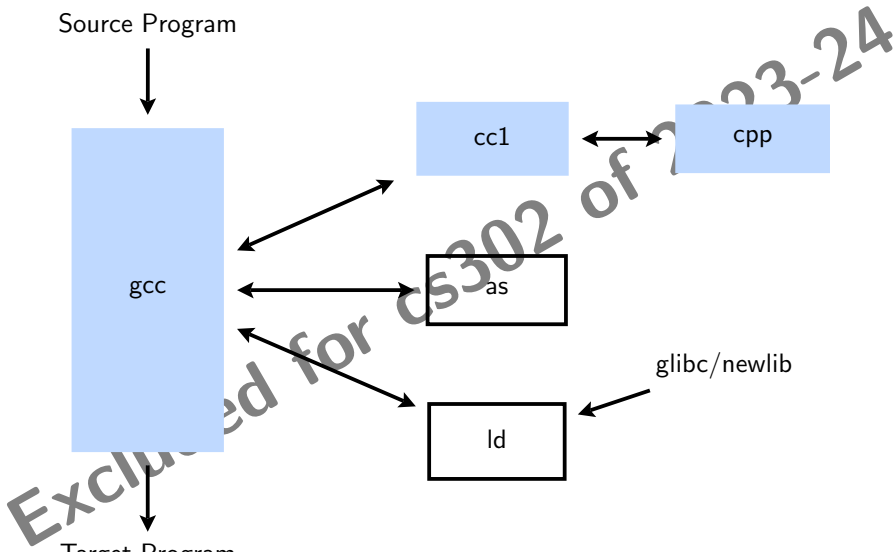
cc1

cpp

as

ld

glibc/newlib





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cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

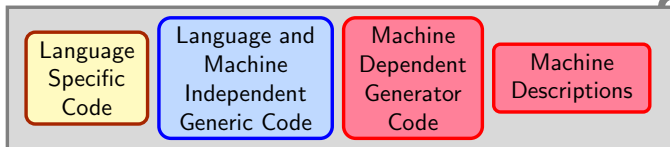
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Architecture of GCC

Compiler Generation Framework

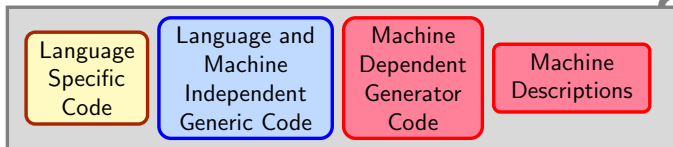


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# The Architecture of GCC

## Compiler Generation Framework



Source Program

Generated Compiler (cc1)

Assembly Program

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cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

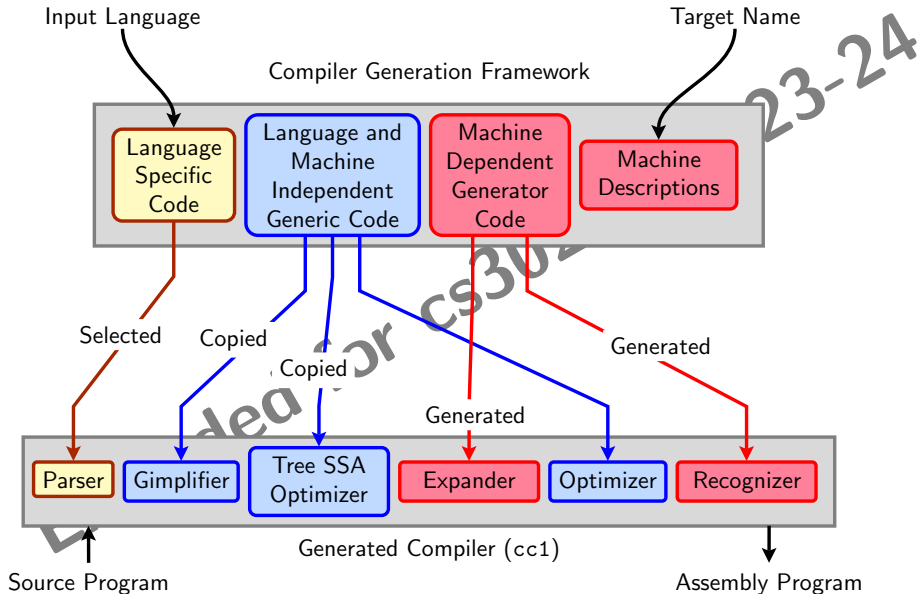
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Architecture of GCC





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

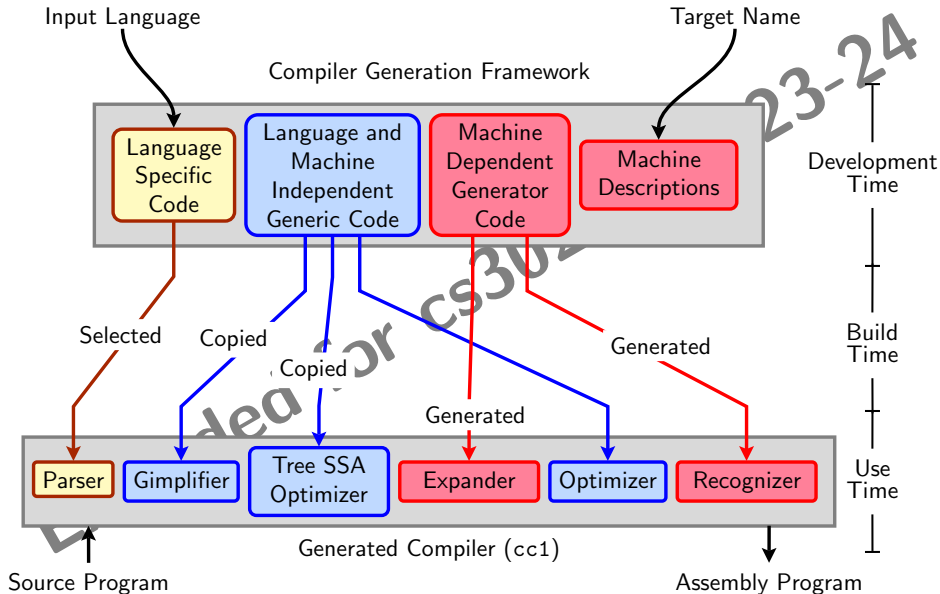
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Architecture of GCC





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

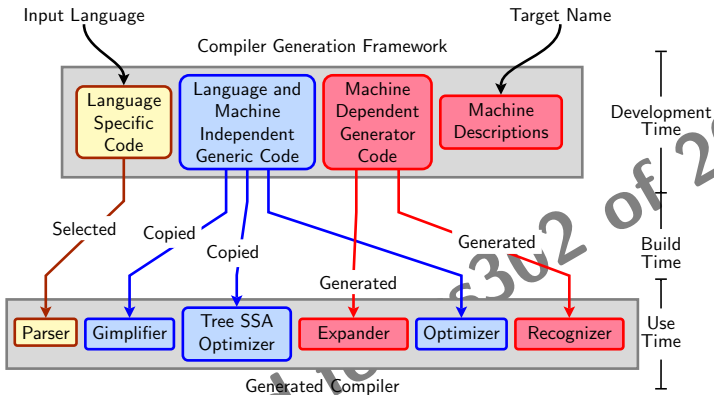
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# GCC Retargetability Mechanism





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

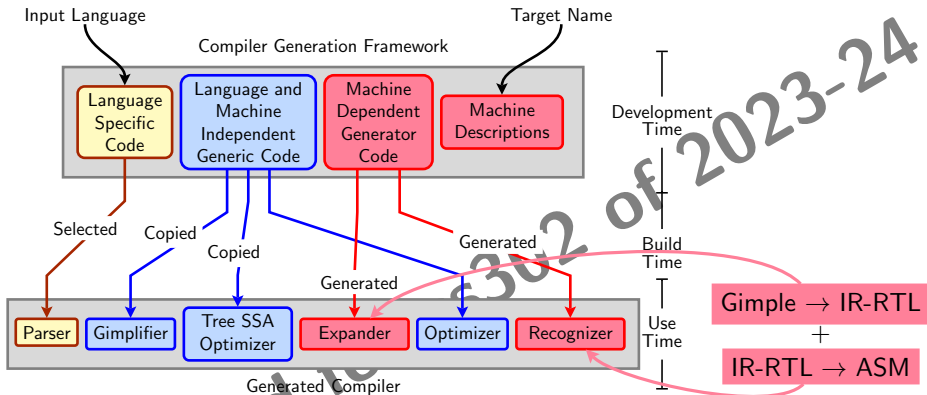
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# GCC Retargetability Mechanism





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

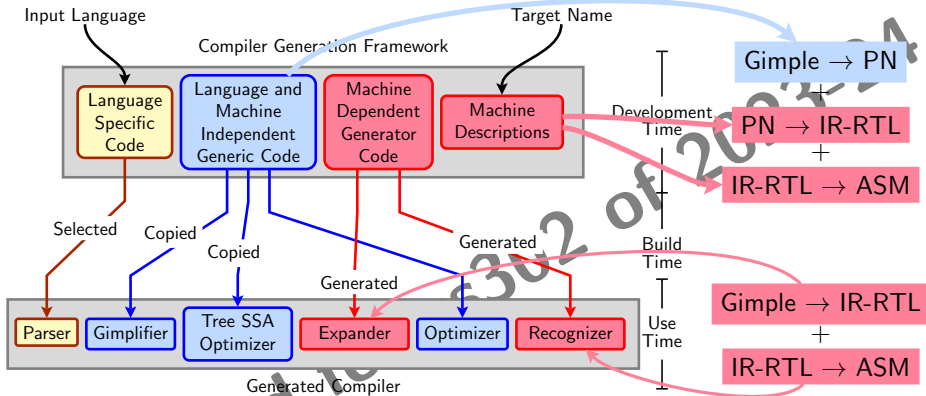
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# GCC Retargetability Mechanism







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

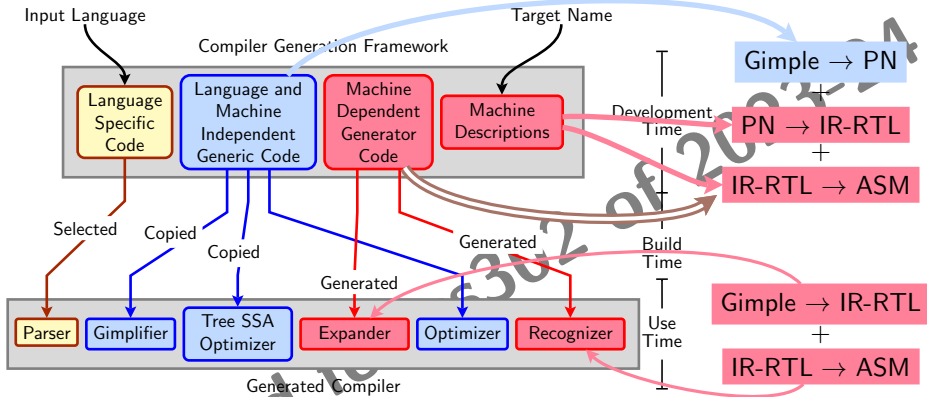
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# GCC Retargetability Mechanism





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

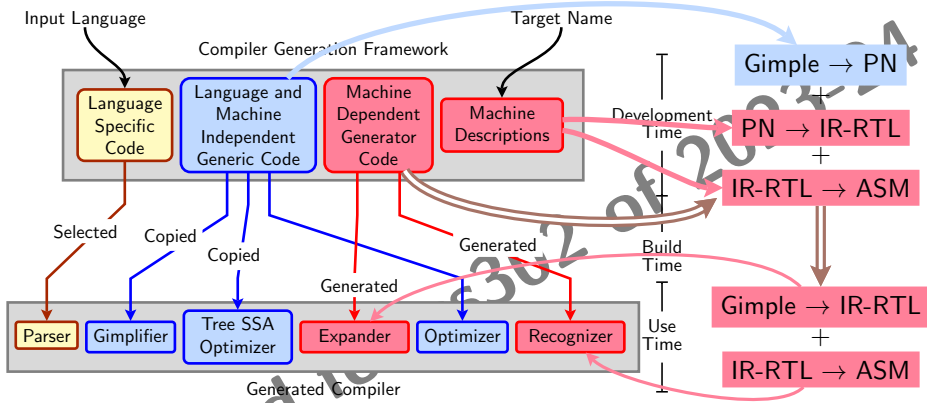
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# GCC Retargetability Mechanism



Excluded



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

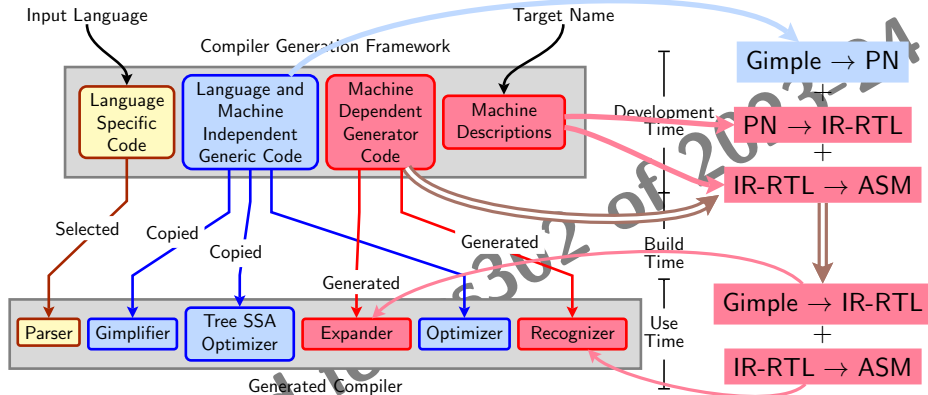
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# GCC Retargetability Mechanism



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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

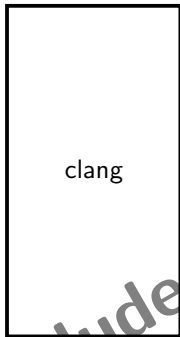
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The LLVM Tool Chain for C

Source Program



Target Program

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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

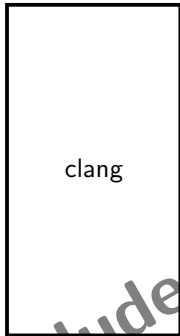
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The LLVM Tool Chain for C

Source Program



Target Program

clag -cc1



Excluded for cs302 of 2023-24



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

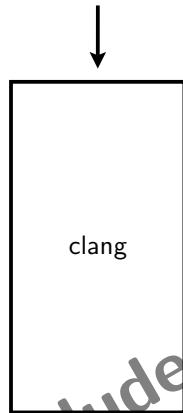
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The LLVM Tool Chain for C

Source Program



clang

clang -cc1

clang -E

Target Program



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

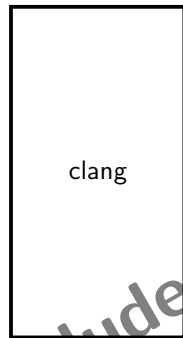
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The LLVM Tool Chain for C

Source Program



Target Program

clang -cc1

clang -E

llvm-as



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

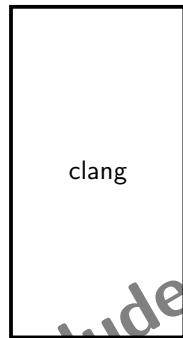
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The LLVM Tool Chain for C

Source Program



clang

clang -cc1

clang -E

llvm-as

lld

Target Program





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

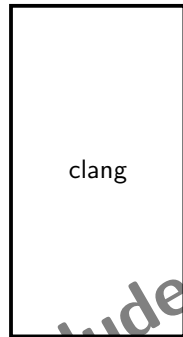
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The LLVM Tool Chain for C

Source Program



Target Program

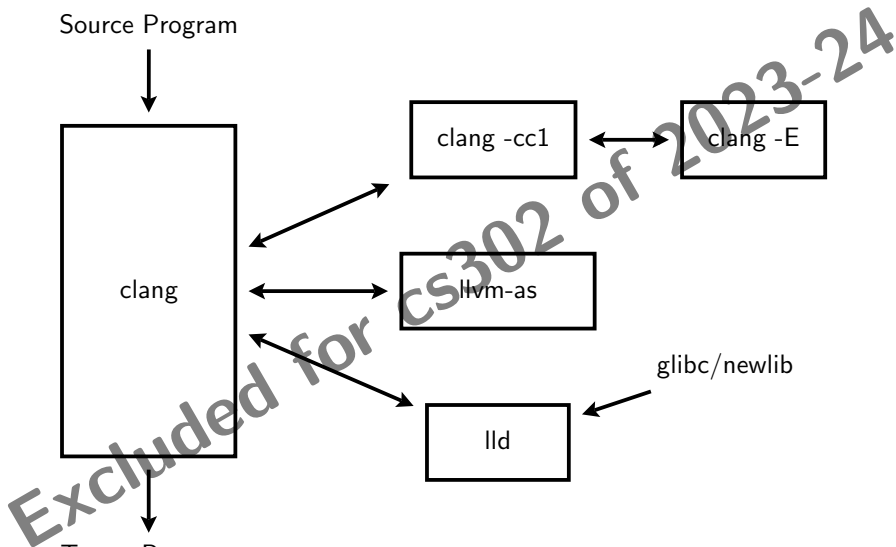
clang -cc1

clang -E

llvm-as

lld

glibc/newlib





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The LLVM Tool Chain for C

Source Program



Target Program

clang -cc1

clang -E

llvm-as

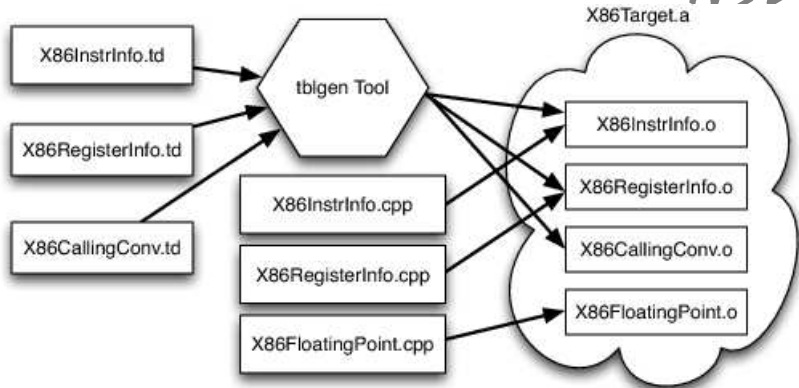
lld

glibc/newlib



# LLVM Retargetability Mechanism

## Simplified x86 Target Definition



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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# 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**.



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Variants of Compiler Builds

$BS = HS = TS$	Native Build
$BS = HS \neq TS$	Cross Build
$BS \neq HS \neq TS$	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

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

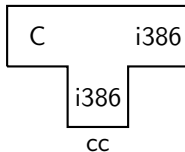
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# T Notation for a Compiler

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

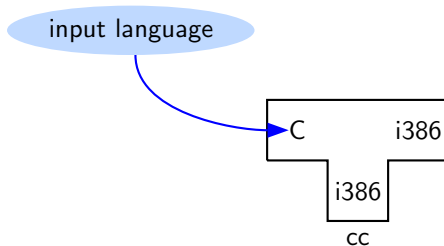
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

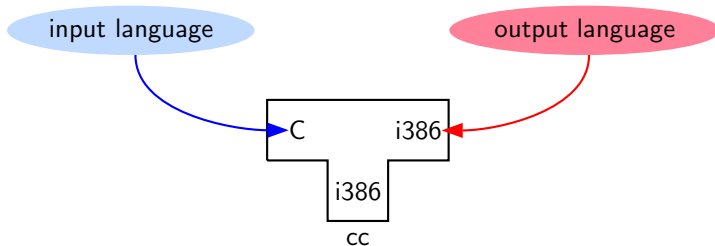
Course Plan

Expectation  
Management





# T Notation for a Compiler



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# T Notation for a Compiler

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

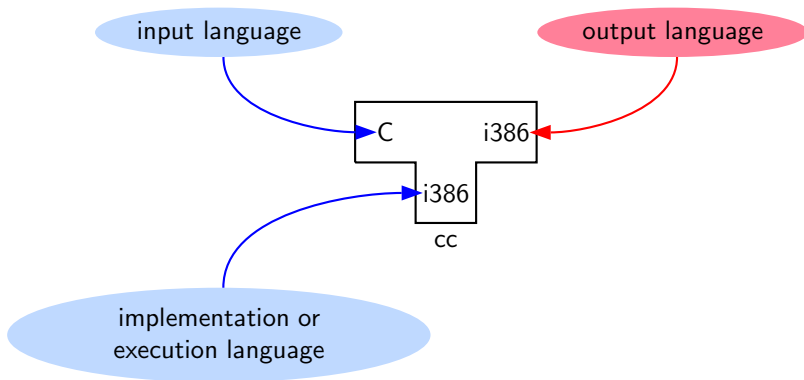
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

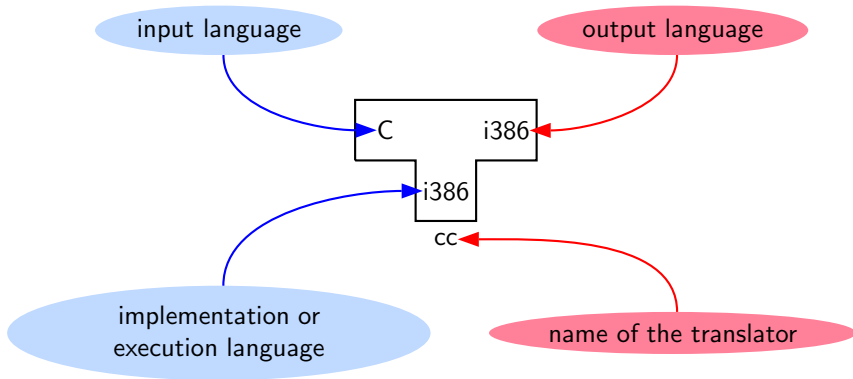
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# T Notation for a Compiler





# Bootstrapping: The Conventional View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

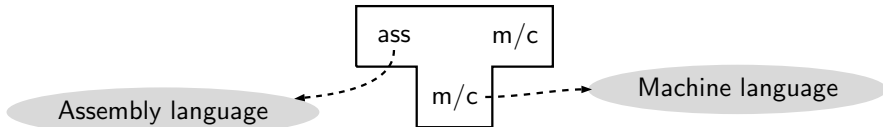
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Bootstrapping: The Conventional View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

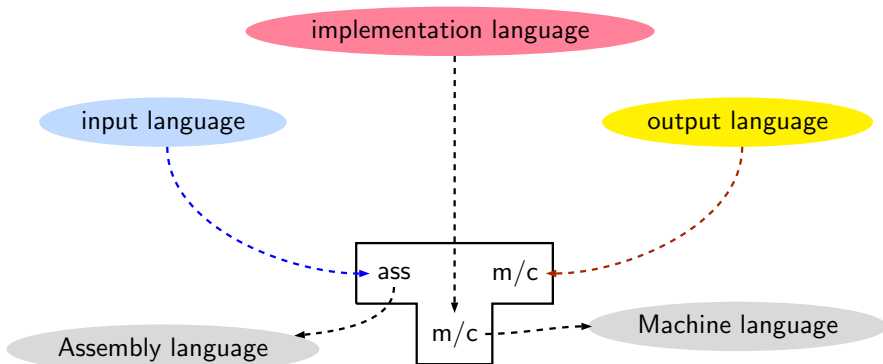
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Bootstrapping: The Conventional View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

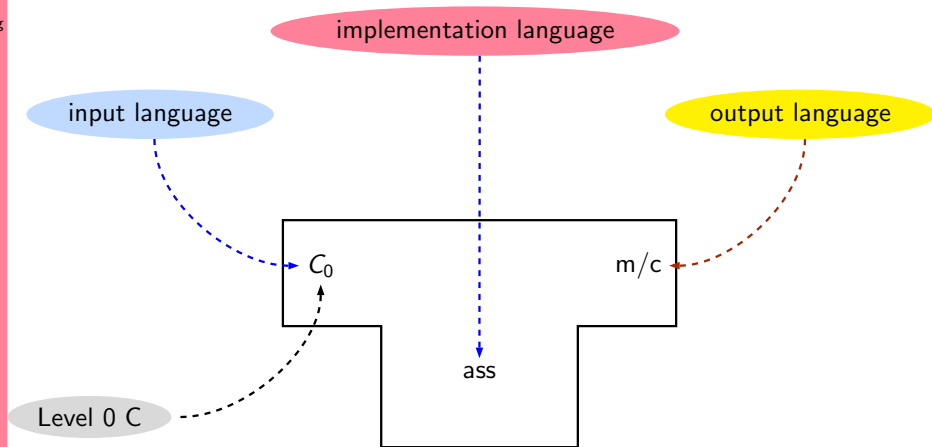
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Bootstrapping: The Conventional View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

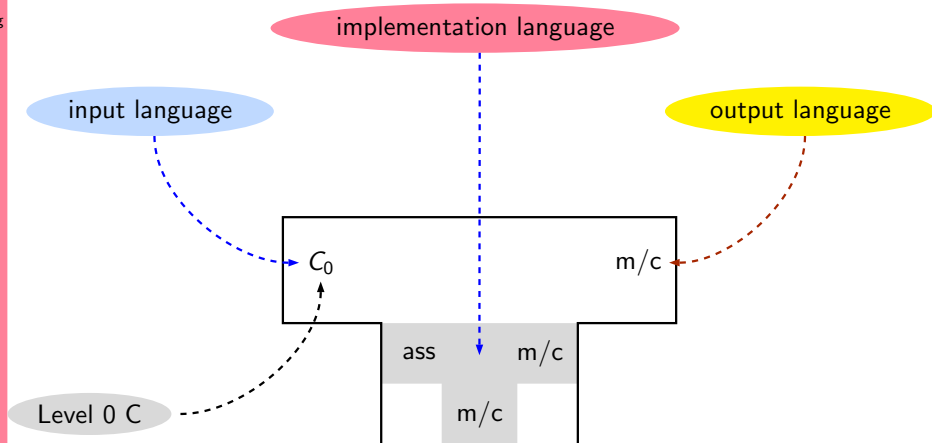
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

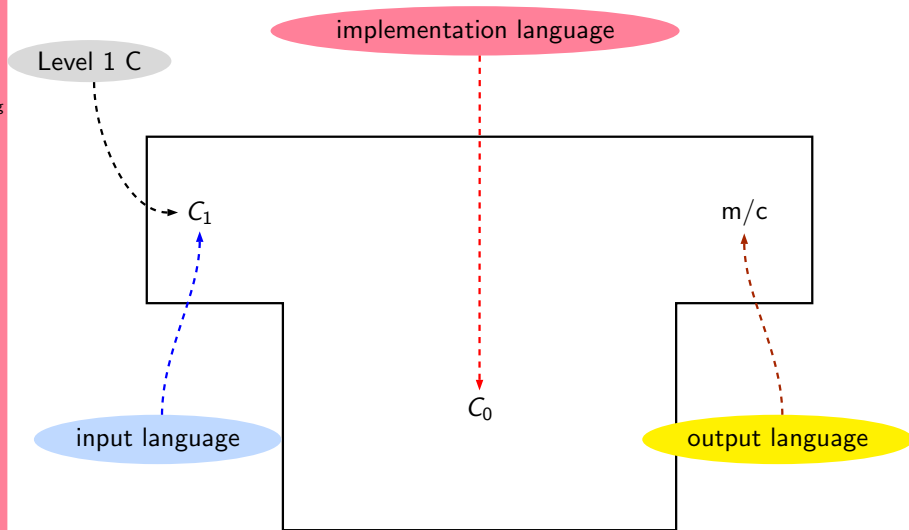
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Bootstrapping: The Conventional View





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

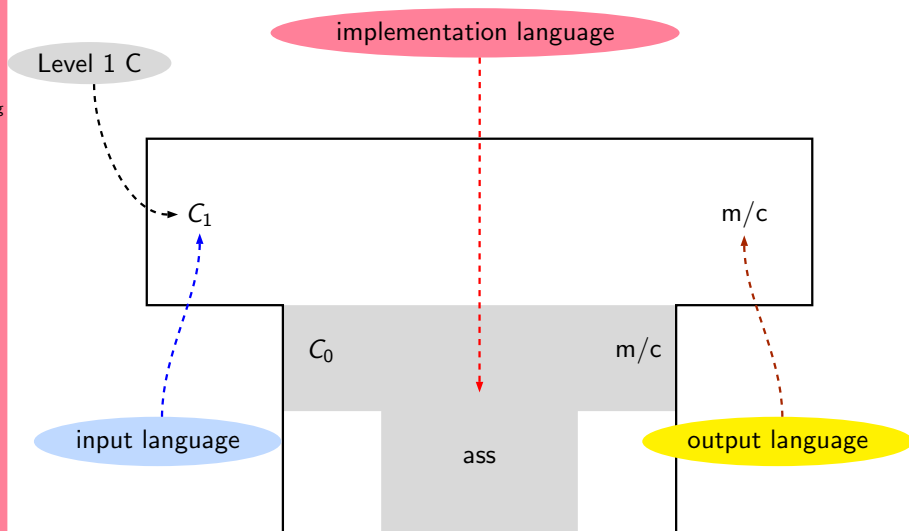
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Bootstrapping: The Conventional View







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

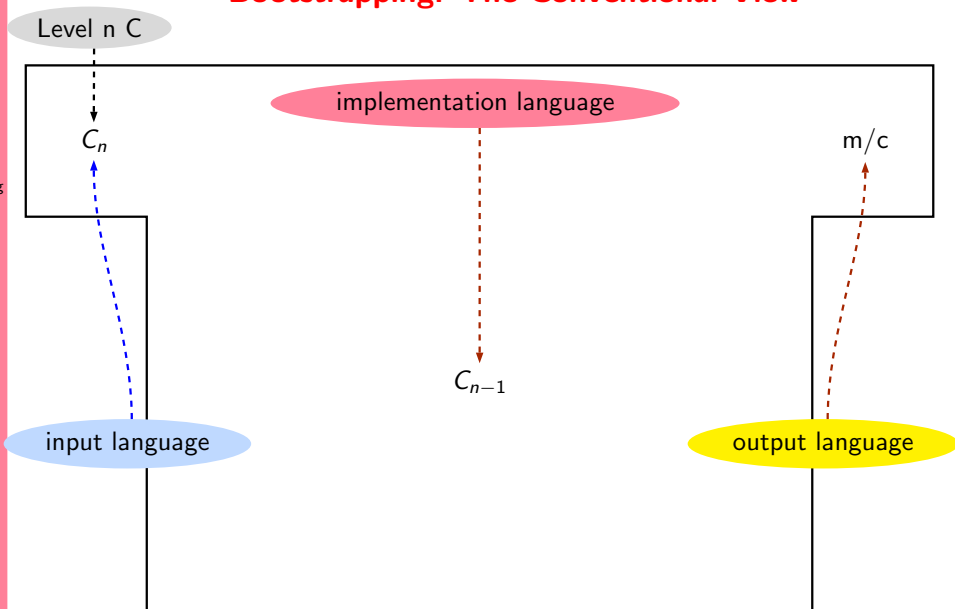
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Bootstrapping: The Conventional View





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

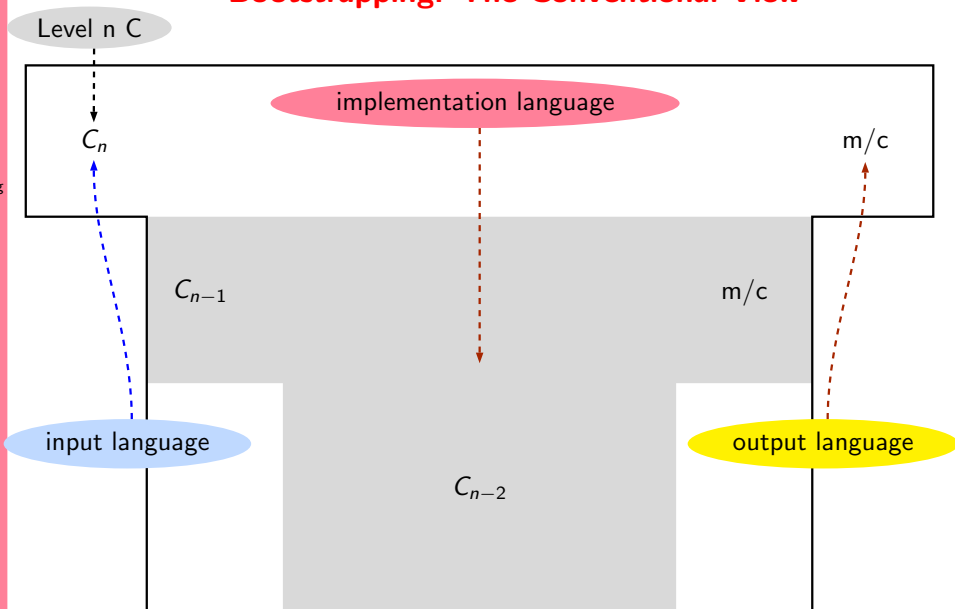
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Bootstrapping: The Conventional View





## Bootstrapping: GCC View

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- 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!



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

**Modern Challenges**

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

**Modern Challenges**

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# 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

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# The Sources of New Challenges

- Languages have changed significantly
  - “The worst thing that has happened to Computer Science is C because it brought pointers with it.” (Frances Allen, IITK, 2007)
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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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  - GPUs, Many core processors, Embedded processors
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- Expectations have changed significantly
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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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  - GPUs, Many core processors, Embedded processors
- Problem sizes have changed significantly
  - Programs running in millions of lines of code
- Expectations have changed significantly
  - Interprocedural analysis and optimization, validation, reverse engineering, parallelization
- Analysis techniques have changed significantly



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Sources of New Challenges

- Languages have changed significantly
  - “The worst thing that has happened to Computer Science is C because it brought pointers with it.” (Frances Allen, IITK, 2007)
- Processors have changed significantly
  - GPUs, Many core processors, Embedded processors
- Problem sizes have changed significantly
  - Programs running in millions of lines of code
- Expectations have changed significantly
  - Interprocedural analysis and optimization, validation, reverse engineering, parallelization
- Analysis techniques have changed significantly
  - Parsing, Data flow analysis, Parallelism Discovery, Heap Analysis



# Compilation for Embedded Processors

IIT Bombay  
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of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

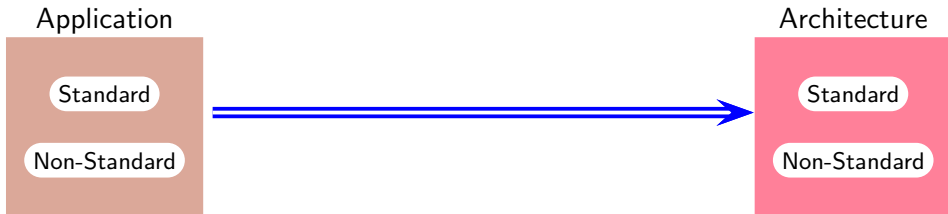
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Compilation for Embedded Processors

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

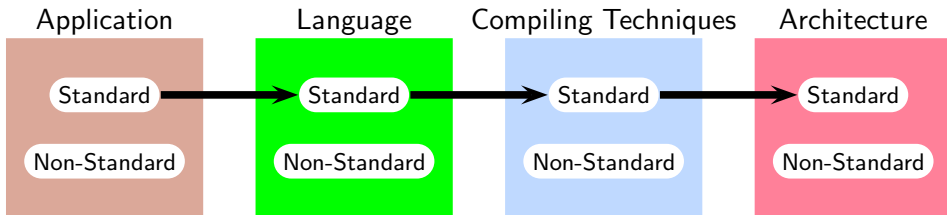
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Compilation for Embedded Processors

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

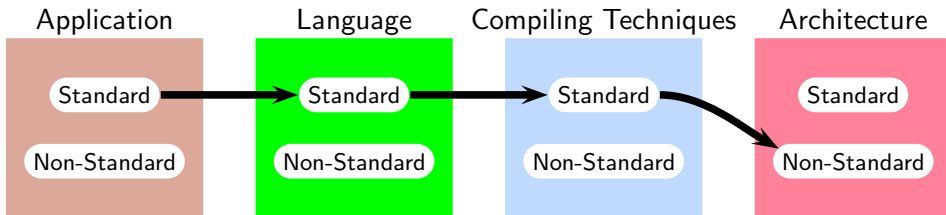
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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



# Compilation for Embedded Processors

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of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

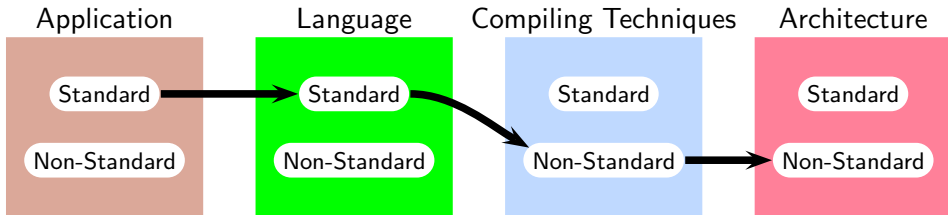
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



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



# Compilation for Embedded Processors

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

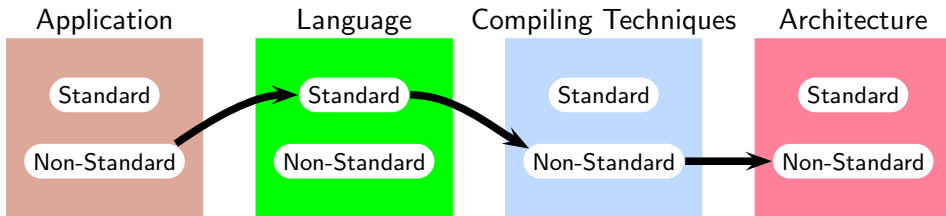
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



- MACs, Special loop instructions





# Compilation for Embedded Processors

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

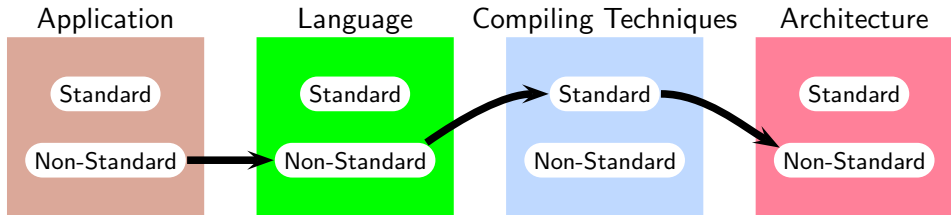
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



- Setting arithmetic modes, circular addressing, special loop instructions



# Modern Challenges: Design issues

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

**Modern Challenges**

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- The IR interface  
What to export? What to hide?
- Retargetability  
Extending to the new version of a processor?  
Extending to a new processor?



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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

**Modern Challenges**

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Modern Challenges: Improving Performance of Programs

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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

**Modern Challenges**

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Modern Challenges: Improving Performance of Programs

- Scaling analysis to large programs without losing precision
  - Interprocedural analysis
  - Pointer analysis
- Increasing the precision of analysis
  - How to interleave different analyses to benefit from each other?
  - How to exclude infeasible interprocedural paths?



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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  - Pointer analysis
- Increasing the precision of analysis
  - How to interleave different analyses to benefit from each other?
  - How to exclude infeasible interprocedural paths?
- Combining static and dynamic analysis
  - Using statically computed information for optimization at run time
  - Using run time information for improving optimizations in the next compilation

(Profile guided optimization aka feedback driven optimization)



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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- Combining static and dynamic analysis
  - Using statically computed information for optimization at run time
  - Using run time information for improving optimizations in the next compilation  
(Profile guided optimization aka feedback driven optimization)
- Inventing more effective optimizations



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Modern Challenges: Improving Performance of Programs

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

- | *Full Employment Guarantee Theorem for Compiler Writers*

([https://en.wikipedia.org/wiki/Full\\_employment\\_theorem](https://en.wikipedia.org/wiki/Full_employment_theorem))

- ( The notion of “best” compiler cannot exist and there is  
endless scope to keep improving  
⇒ For every compiler, a better compiler can be written

(Profile guided optimization aka feedback driven optimization)

- Inventing more effective optimizations



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## 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 parallelism
  - Doall, Async, Threads, Synchronization, Fork/Join, Lock/Unlock, Mutex, Semaphores
  - Some features 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/Meltdown attacks)
- 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

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# 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

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

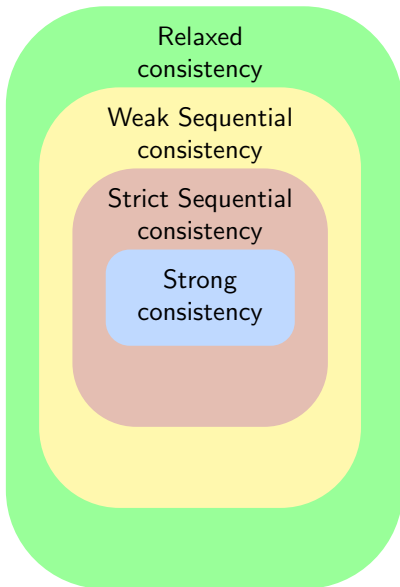
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Classes of Memory Models



Model	Data dependence across threads	Data dependence within threads
SC	Preserved	Preserved
SSC	Not preserved	Preserved
WSC	Not preserved	Not preserved (no reordering but writes may not be available)
RC	Not preserved	Not preserved (reordering of instructions)



# Architecture Feature Influencing Programming Language

A concurrent program

Initially  $X = Y = 0$

$a = X$

$b = Y$

$Y = 1$

if( $b$ )  $X = 1$

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

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Architecture Feature Influencing Programming Language

A concurrent program

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

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

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 sequential consistency.** Result of writes are available instantaneously

Both prints of `a` must read the value 1

⇒ Only one result is possible: 1, 1

- **Weak sequential consistency.** Result of writes may be available with a delay

The first print of `a` may read 0

⇒ Both 0, 1 and 1, 1 are possible

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Architecture Feature Influencing Programming Language

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

A concurrent program

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$Y = 1$

if( $b$ )  $X = 1$

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

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



# Architecture Feature Influencing Programming Language

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

A concurrent program

Initially  $X = Y = 0$

$a = X$

$Y = 1$

$b = Y$

if( $b$ )

- Variables  $a$  and  $b$  are thread-local variables

and global variables

Why is this useful?

Relaxed

Out of order execution offers more opportunities of keeping the pipeline

full, thereby increasing the throughput

can be interchanged

$Y = 1$

$b = Y$

$b? X = 1$

$a = X$

$a = b = 1$

- 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





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# 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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

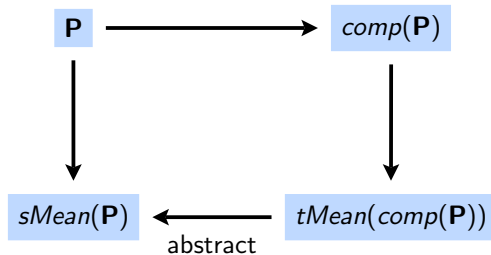
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Compiler Verification

Formalize and verify the following diagram for every source program  $P$



$comp$  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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

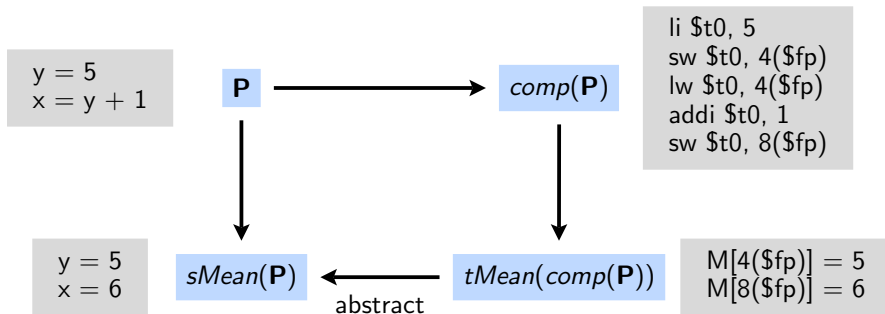
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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# Difficulties in Compiler Verification

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- 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



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cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

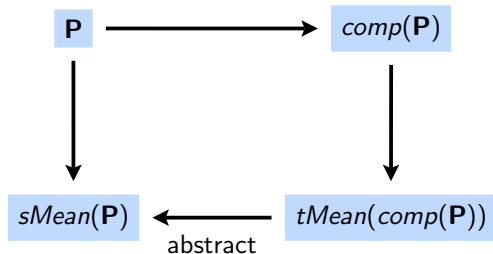
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Translation Validation

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



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IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

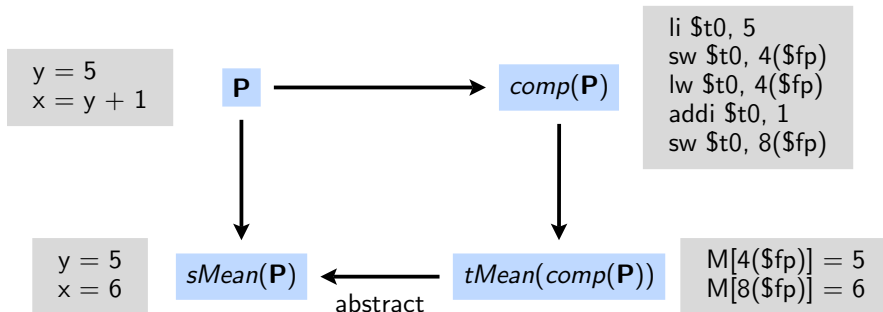
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

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# Translation Validation

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- 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 explainability for guaranteeing soundness 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?

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



# Modern Challenges: New non-PL Technologies



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

**Modern Challenges**

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- Can we use LLMs to scale program analysis and optimizations?
  - It may be possible to use LLMs to analyse smaller chunks of code
  - Some light-weight analysis can be used to connect the results of analysis of two different chunks of code



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Moral of the Story

Achieving  
Performance

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



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

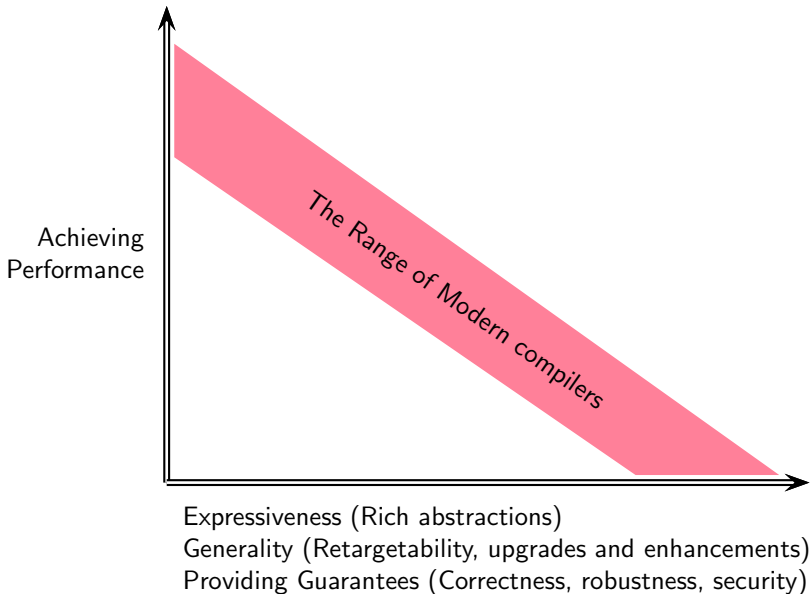
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# The Moral of the Story





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

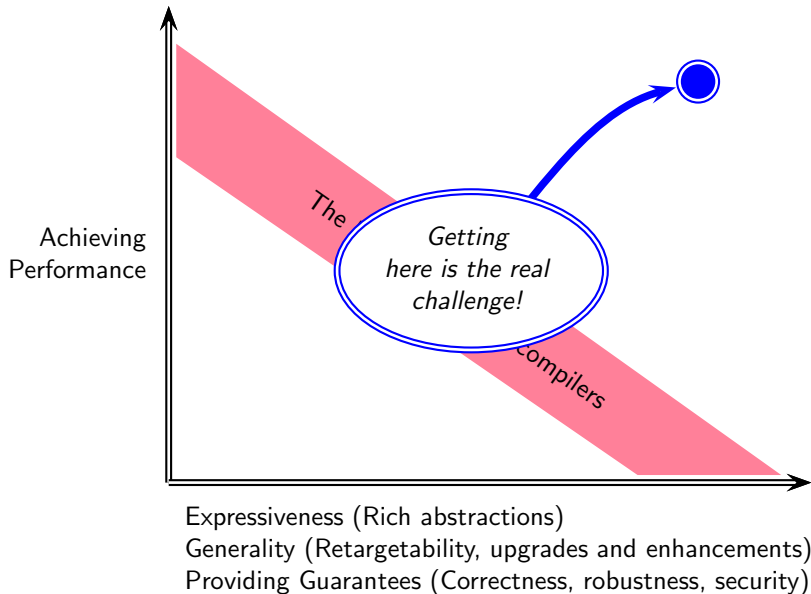
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## The Moral of the Story





**IIT Bombay**  
**cs302: Implementation**  
**of Programming**  
**Languages**

**Topic:**

**Compilation Overview**

**Section:**

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

**Incremental**  
**Construction of**  
**Compilers**

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

**Incremental  
Construction of  
Compilers**

Course Plan

Expectation  
Management

# Incremental Construction of Compilers



# In Search of Modularity in Compilation

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

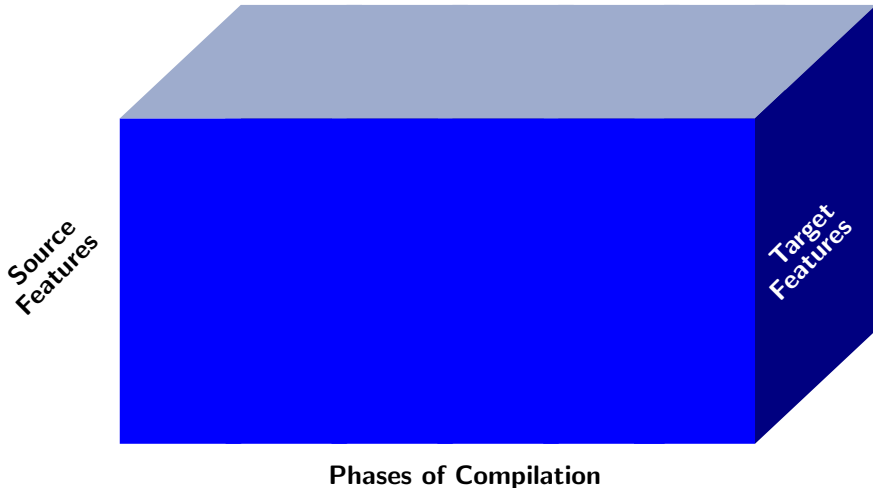
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# In Search of Modularity in Compilation

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

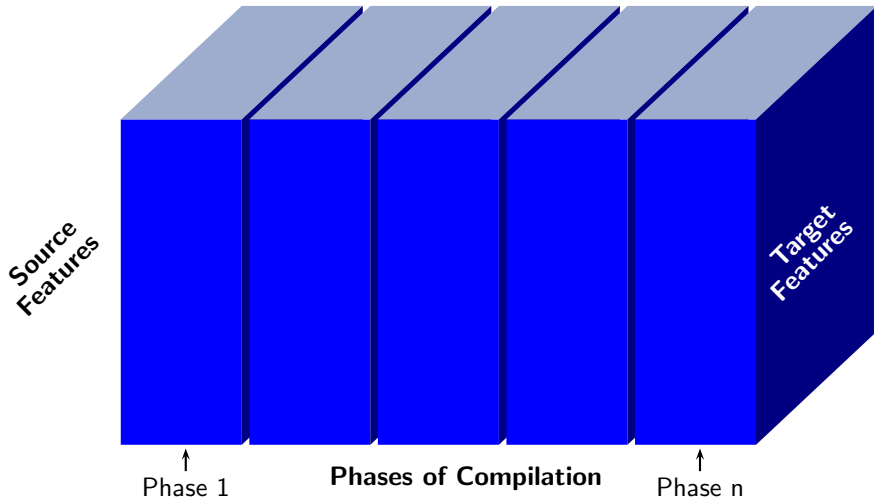
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management







# In Search of Modularity in Compilation

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

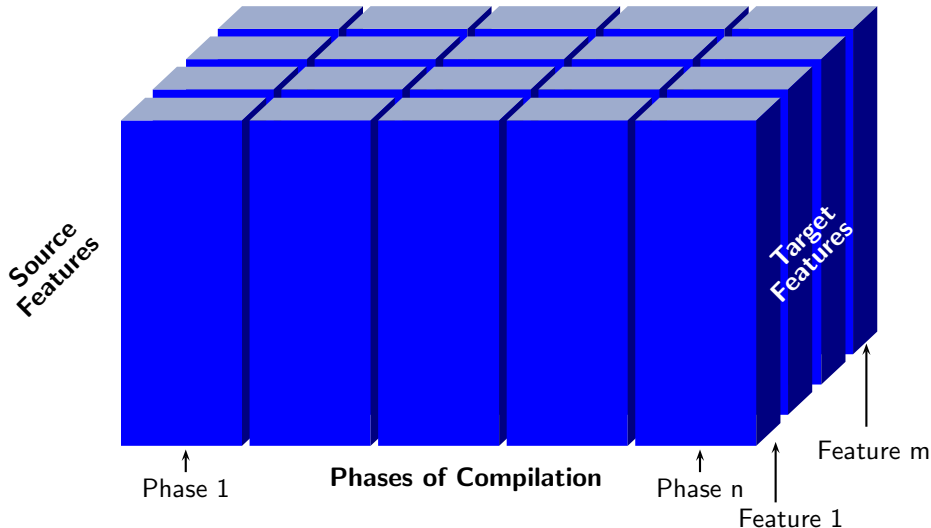
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# In Search of Modularity in Compilation

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

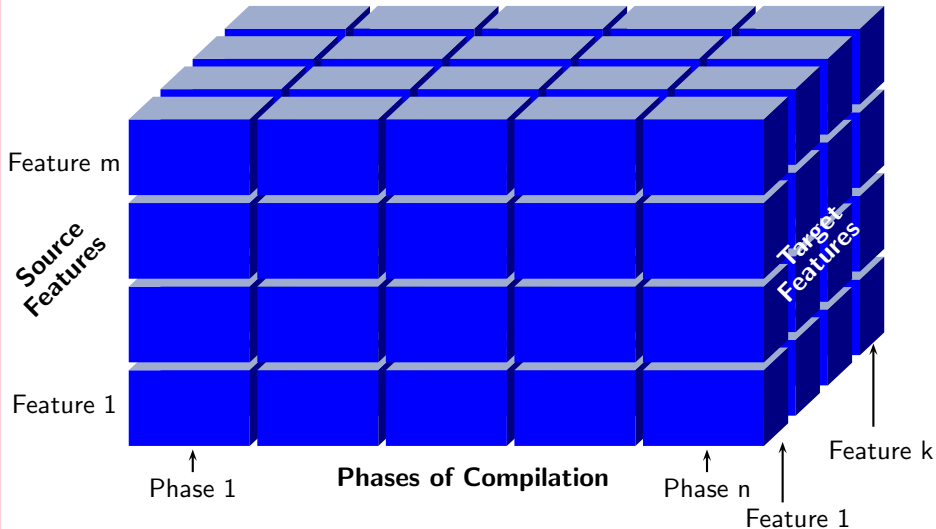
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# In Search of Modularity in Compilation

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

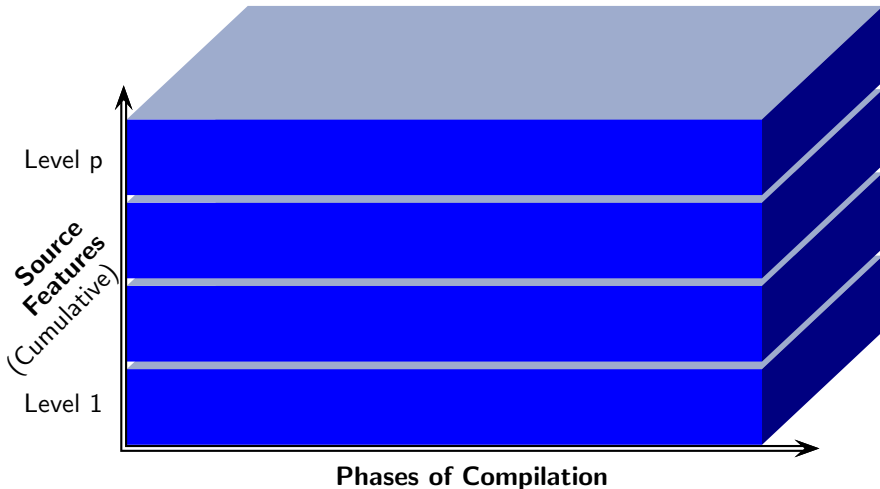
Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management





# Language Increments

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

**Incremental  
Construction of  
Compilers**

Course Plan

Expectation  
Management

Assignments with  
simple RHS

Level 1



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

**Incremental  
Construction of  
Compilers**

Course Plan

Expectation  
Management

# Language Increments

Arithmetic Expressions

Assignments with  
simple RHS

Level 1

Level 2



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

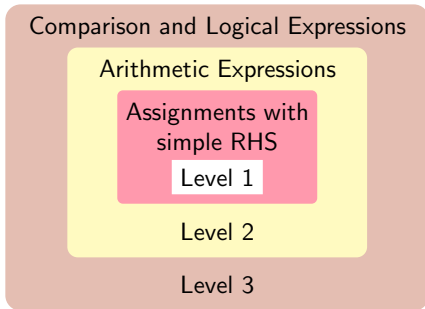
Modern Challenges

**Incremental  
Construction of  
Compilers**

Course Plan

Expectation  
Management

# Language Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

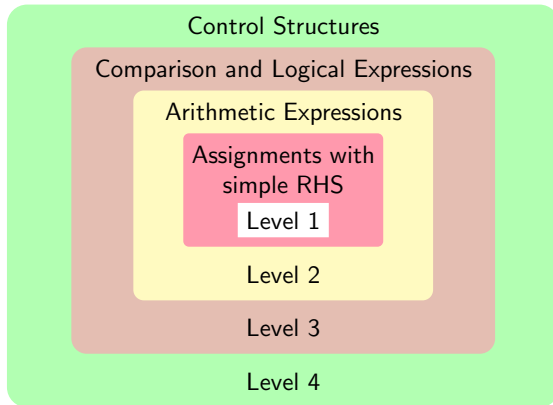
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Language Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

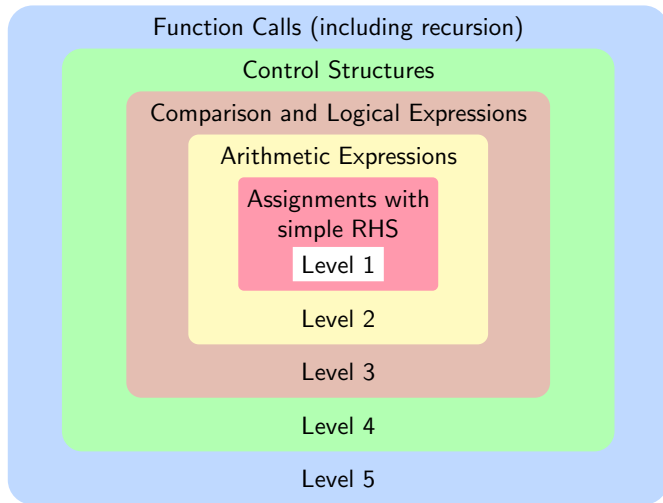
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Language Increments







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

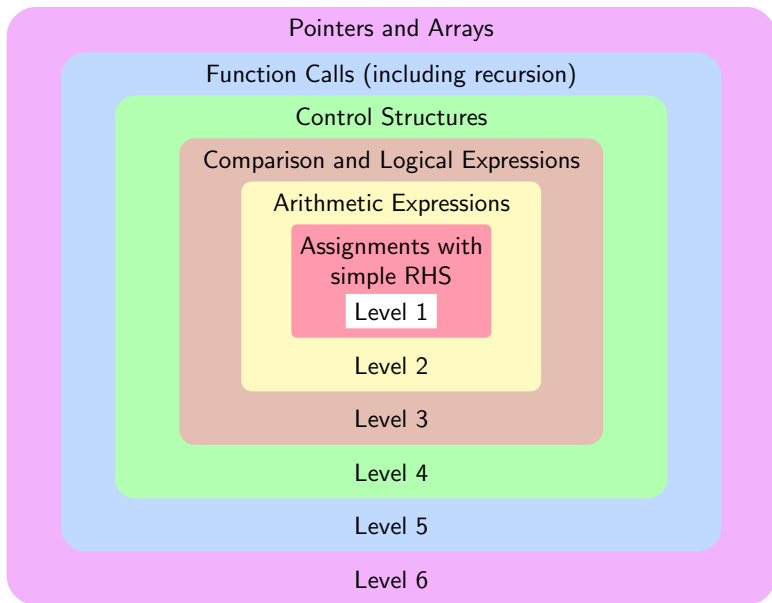
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Language Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

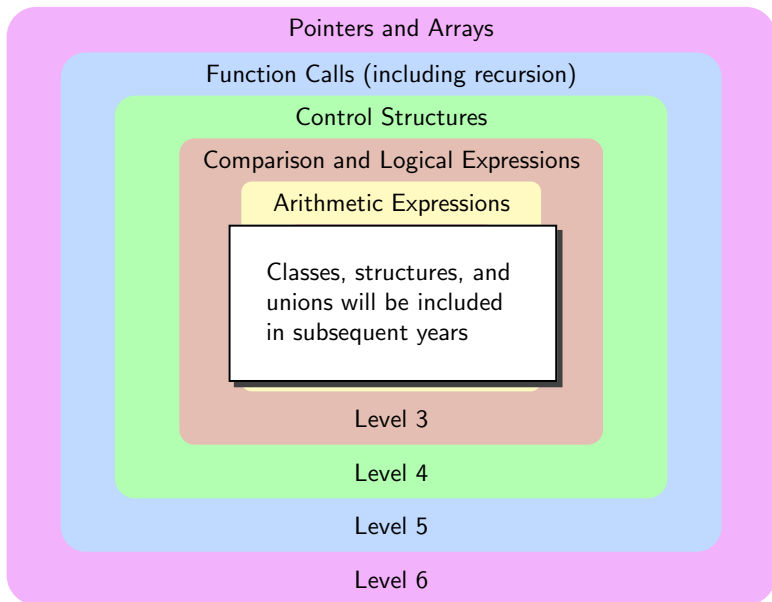
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Language Increments





**IIT Bombay**  
**cs302: Implementation**  
**of Programming**  
**Languages**

**Topic:**

**Compilation Overview**

**Section:**

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

**Course Plan**

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

**Course Plan**

Expectation  
Management

# Course Plan



# cs302 Coverage and Pedagogy

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- Coverage
  - Scanning, Parsing, Static Semantics, Runtime Support, Code Generation
  - Code Optimization, Register Allocation (may be omitted)
- Pedagogy
  - Lectures
  - Slides will be made available on moodle
  - Asynchronous discussions on moodle discussion forum
  - Tutorial problems on moodle
- Evaluation
  - Two quizzes, mid sem, end sem, and class participation



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## cs316 Coverage

- Coverage
  - Incremental construction of SCLP
  - Reference implementation with some test cases will be provided
- Pedagogy
  - Five assignments common to all students
    - Implementation of additional features may fetch bonus credit
    - Independent projects may be allowed to replace some of the assignments
  - Roughly two weeks per submission
  - Work do be done in a personalized VM in the lab machines or on your laptop (requires x86)
  - Groups of two
- Evaluation will be by running diff on the output
  - Standard file names and directory names must be used
  - It will not be possible to entertain violations
  - Use your creativity inside your code, not in file names, Makefile commands and program output



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

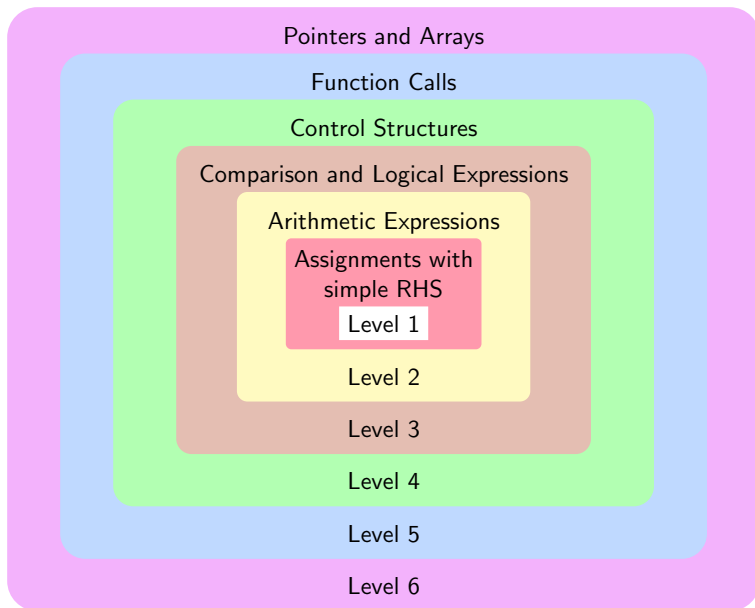
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# SCLP Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

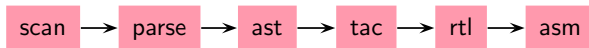
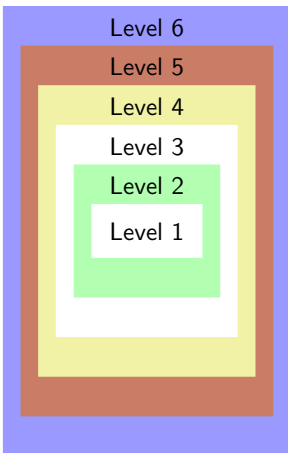
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment







IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

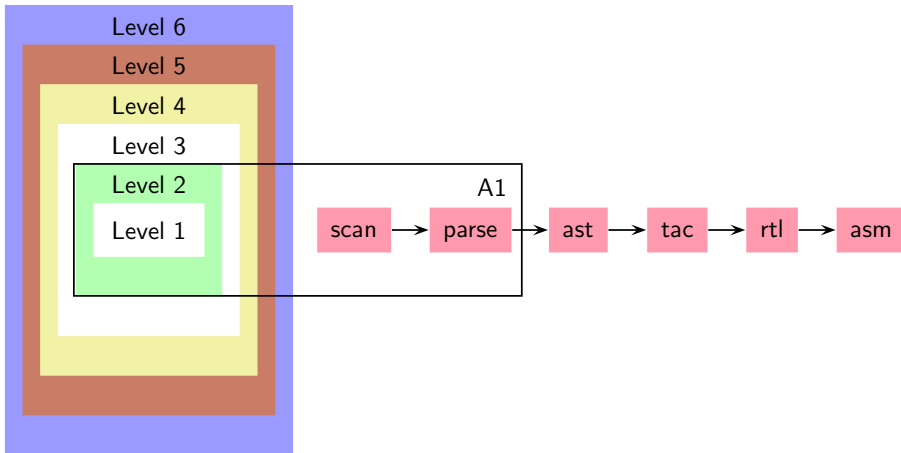
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Proposed Assignment Plan: Incremental Construction

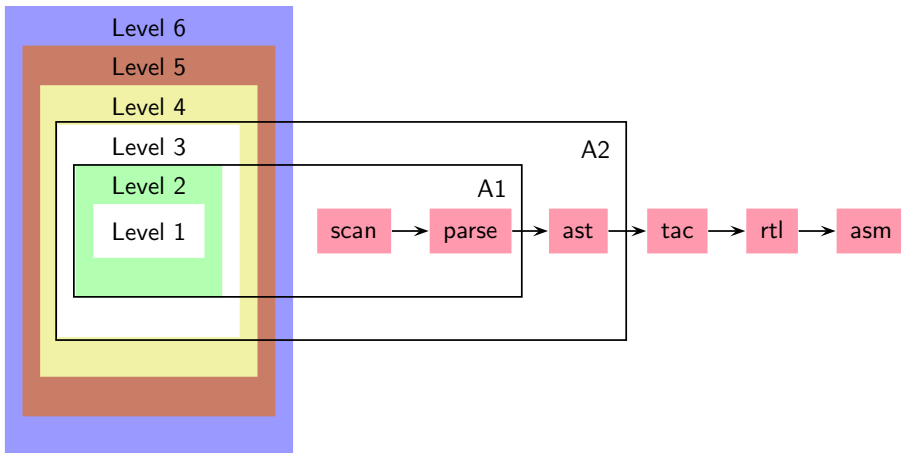
A series of assignments; each assignment builds on the previous assignment





# Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:  
Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

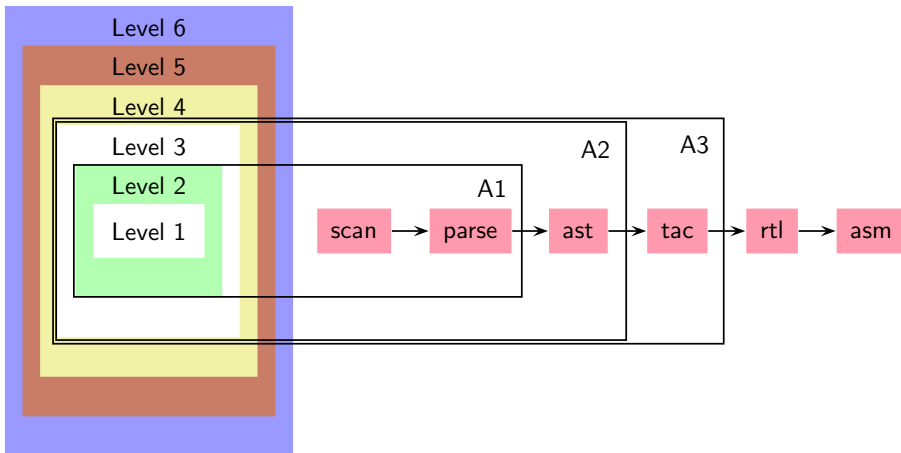
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

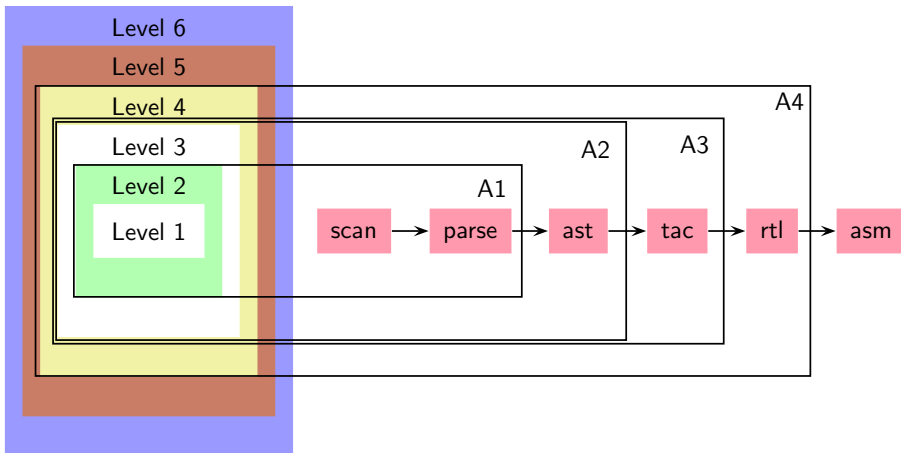
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Proposed Assignment Plan: Incremental Construction

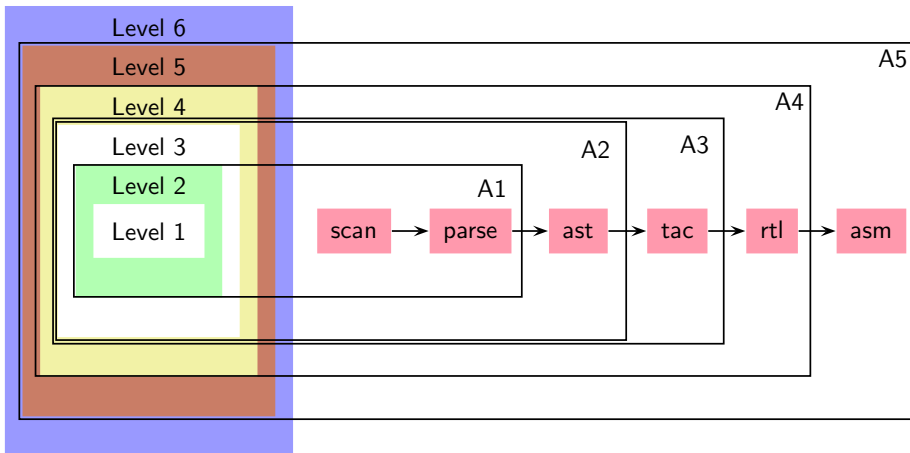
A series of assignments; each assignment builds on the previous assignment





# Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

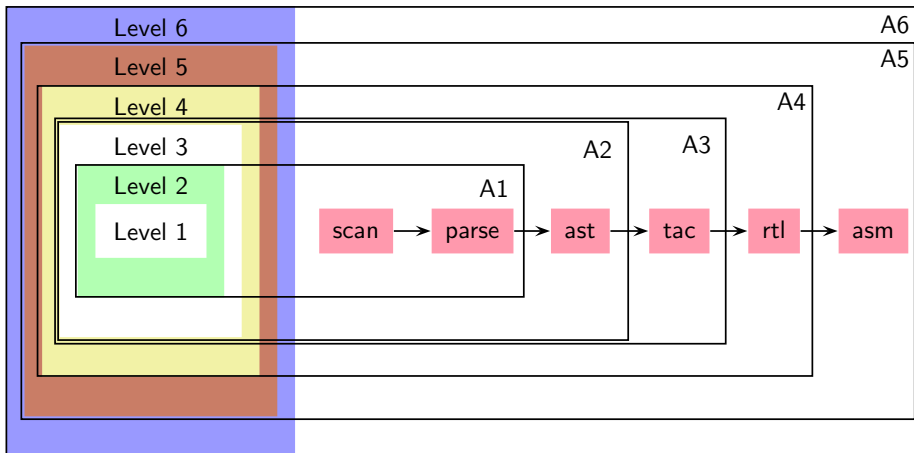
Course Plan

Expectation  
Management



# Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

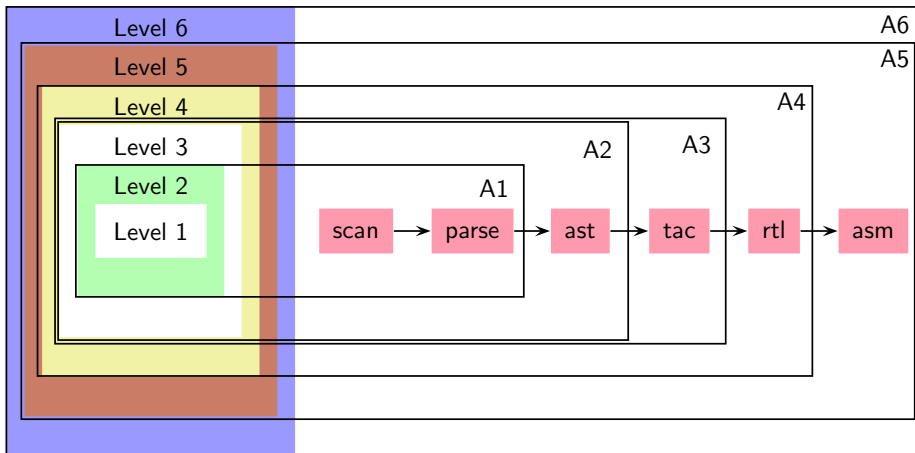
Course Plan

Expectation  
Management



# Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

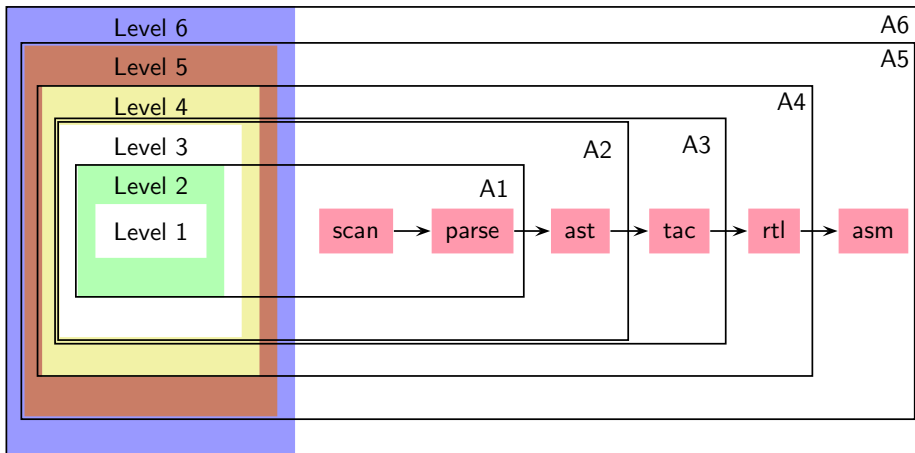
Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Proposed Assignment Plan: Incremental Construction

A series of assignments; each assignment builds on the previous assignment



Exact number will be decided in due course but A1 to A6 should be doable





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

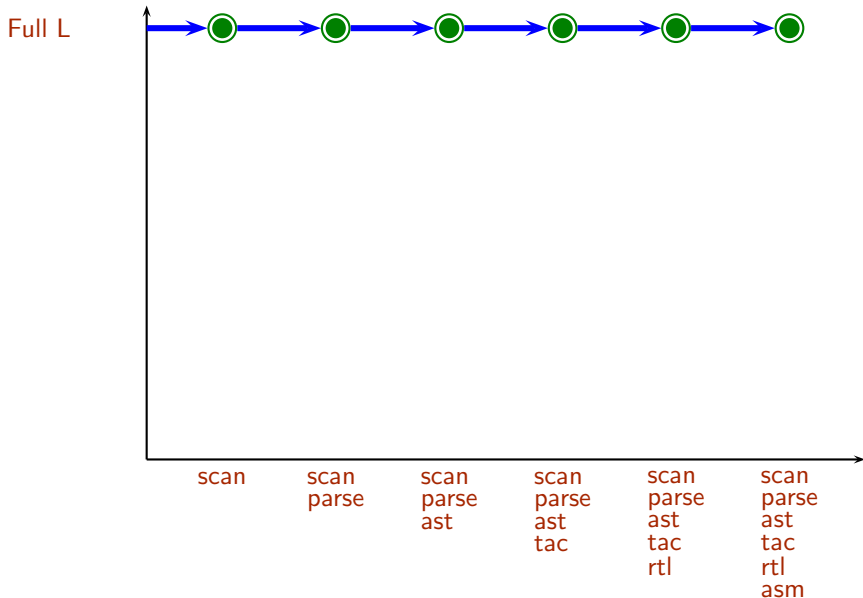
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

# Conventional Increments Vs. Proposed Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

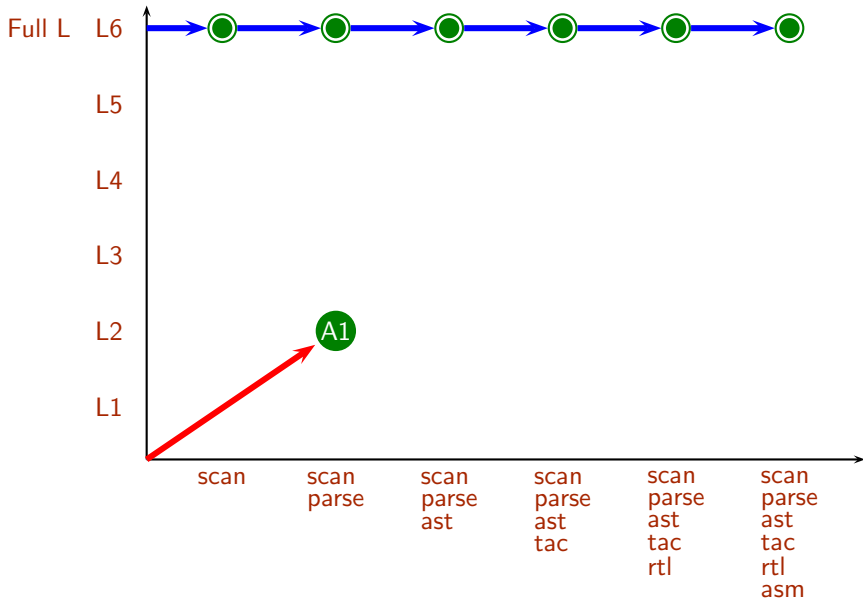
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Conventional Increments Vs. Proposed Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

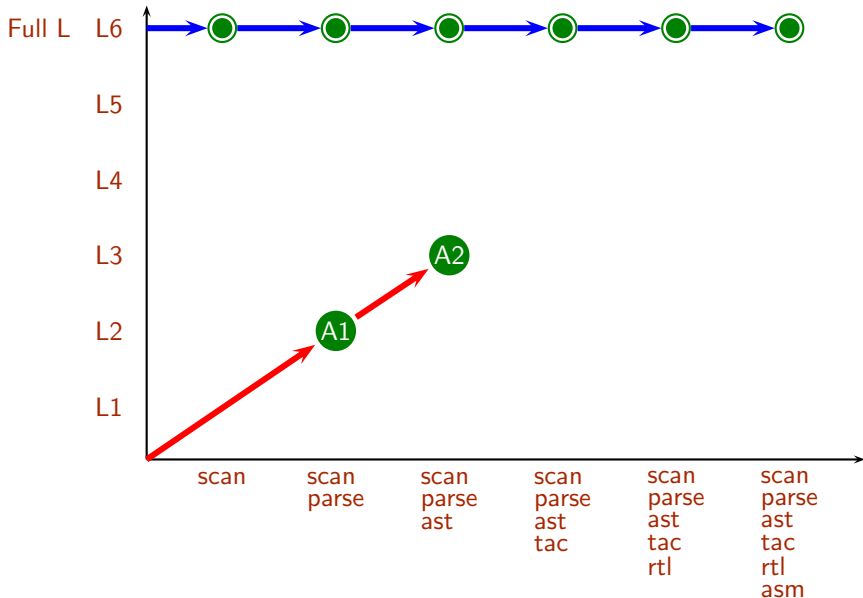
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Conventional Increments Vs. Proposed Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

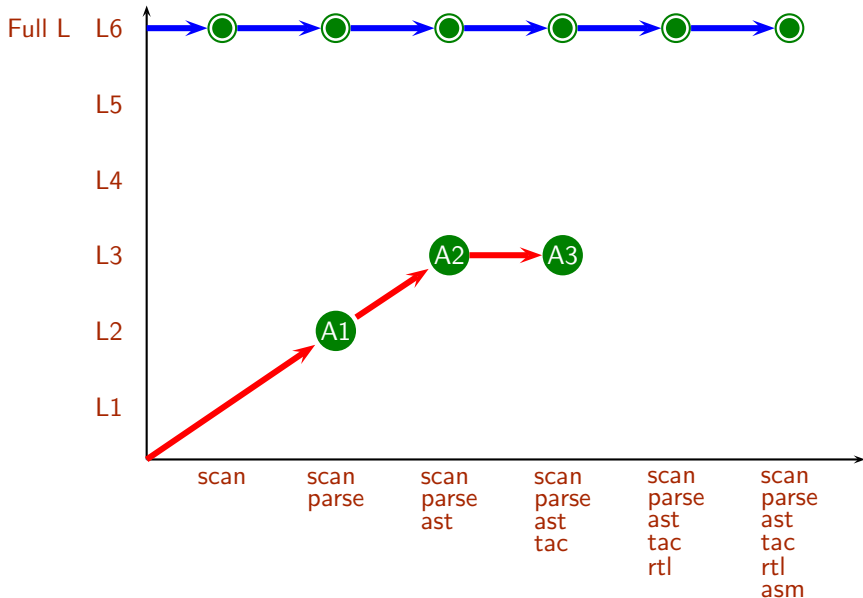
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Conventional Increments Vs. Proposed Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

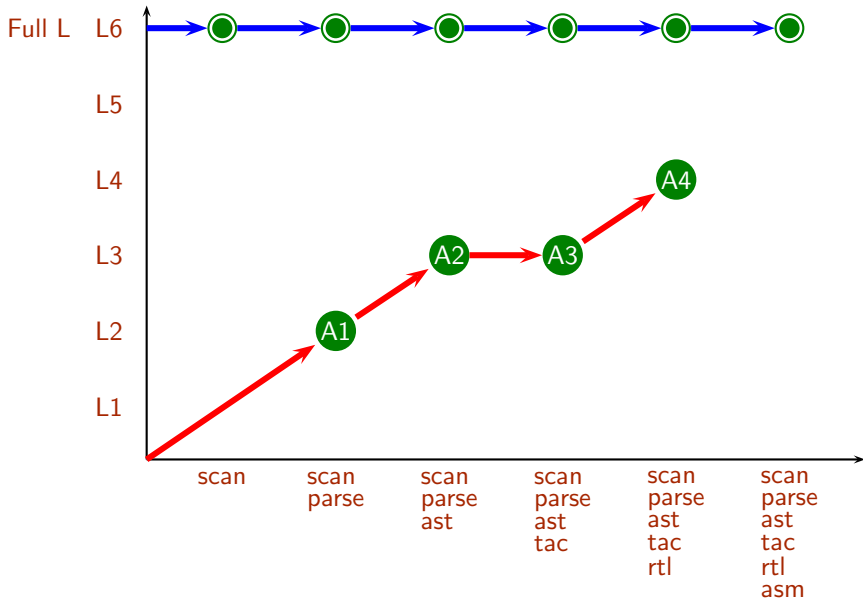
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Conventional Increments Vs. Proposed Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

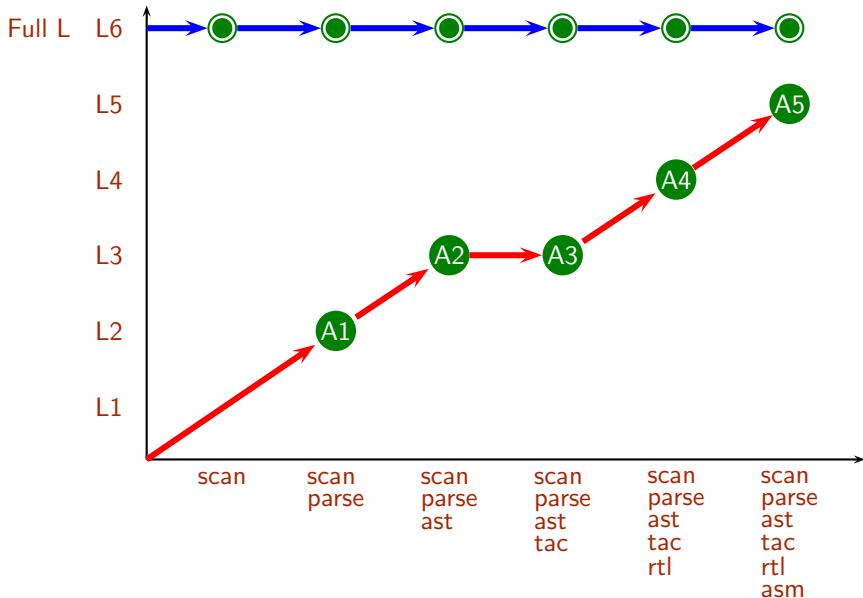
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Conventional Increments Vs. Proposed Increments





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

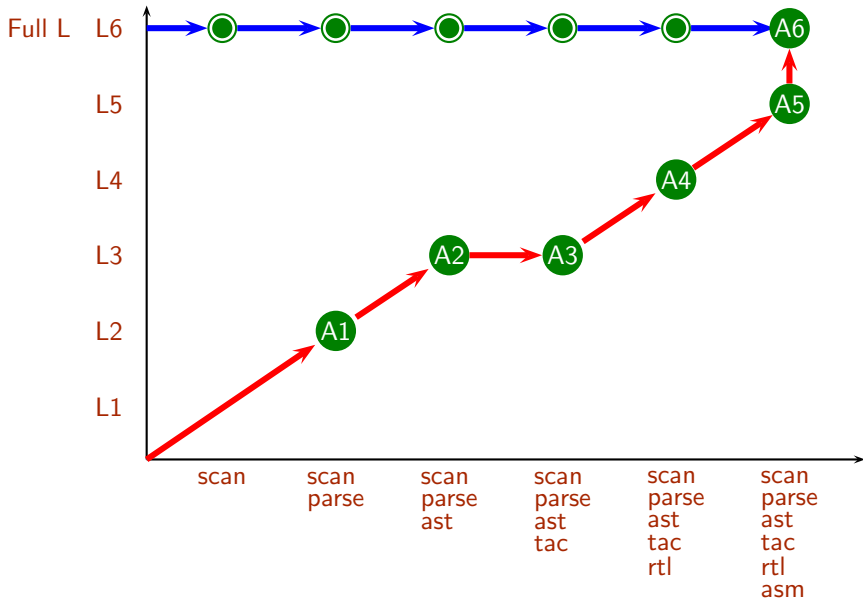
Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Conventional Increments Vs. Proposed Increments



# Evaluation Plan and Grading



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- cs302  
Mid-Sem (30%) and End-Sem (40%)  
Quizzes (20%)  
Class Participation (10%)  
A viva may be factored in later
- cs316  
Five assignments to be done on coffre (90%)  
Class Participation (10%)  
A viva may be factored in later





**IIT Bombay**  
**cs302: Implementation**  
**of Programming**  
**Languages**

**Topic:**

**Compilation Overview**

**Section:**

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

**Expectation**  
**Management**



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

**Expectation  
Management**

# Expectation Management



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## FAQ (1)

- Q. Can I form a group of 3 for cs316 assignments?  
A. The credit of each student will be proportionately reduced
- Q. Can I form a group of 1 for cs316 assignments?  
A. No, I do not want to increase the number of groups
- Q. I do not have an x86 machine. What should I do?  
A. Use lab machines
- Q. Why can't I take my code out of coffre server even at the end of the course?  
Your take away from the course is your learning and not your code. Besides, we have had students publishing their code on public repositories which conflicts with the goals of the course for subsequent batches



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## FAQ (3)

- Q. I sent a message to you on MS Teams but did not get any response!

A. I don't use MS Teams

- Q. I sent a message to you on Moodle but did not get any response!

A. Post queries on moodle forums so they get tracked by multiple people

- Q. How do we communicate with you outside of the class?

A. Talk me just after the class, minimize the email communication

For issues that are likely to be of common interest, please write on moodle discussion forum

For issues that are strictly personal, send an email to [uday@cse.iitb.ac.in](mailto:uday@cse.iitb.ac.in) with a copy to [nisha@cse.iitb.ac.in](mailto:nisha@cse.iitb.ac.in)

The subject header of every email sent to me must contain the word “cs302” or “cs316” otherwise the mail may be mis-classified and may not be attended to for a long time



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## FAQ (5)

- **Q. Is attendance compulsory?**

A. Yes. Both attendance and participation is compulsory. It can be in the form of asking questions in the class, discussion meetings, on moodle forums, pointing out bugs in the reference implementation, responding to the posts made by others etc.

In the absence of any such participation, I will have to use attendance as a proxy

- **Q. Why do you insist on students attending and participating? Why can't we learn independently?**

A. Studying is like evaluating expressions that have lots of free variables. Regular participation ensures that these variables are bound to right values

Familiarity with the notations and conventions used in the class simplifies understanding and evaluation and makes grades consistent and reliable



IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

## Things that I Discourage and Disapprove

- Asking questions only in the last two days before exams

I will not provide clarifications two days before the exam

- Direct communication with the TAs about policies, evaluations, requests for extensions, or marks

All communication must be with me. TAs are not authorized to respond to you directly on these matters without my explicit permission to do so

- Expecting instantaneous responses, making a request at the last moment

Email responses will be provided in batch mode. And there may be no response to some emails. Please do not remind me

- Trying to push your luck by assuming that requests for concessions can only give benefit but no harm

I will listen sympathetically, and may explain the rationale behind my decision but will not get into a discussion nor will try to convince you

- Feigning ignorance about the policies that have been described clearly in slides, emails, or moodle announcements

I have no sympathy for such students – sorry, bad luck!



# Further Expectation Management

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- Things that I like and strongly encourage
  - Asking questions, reporting bugs in reference implementation
  - Free, frank, and respectful communication
- Thing that I detest and despise
  - Cheating
  - Grade Litigation



# Cheating

IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:

Compilation Overview

Section:

Outline

Introduction to  
Compilation

An Overview of  
Compilation Phases

Compilation Models

Modern Challenges

Incremental  
Construction of  
Compilers

Course Plan

Expectation  
Management

- Collaboration in learning or discussions about your code are fine  
But your answers in exam and your code in submit **MUST BE YOURS**
- No compromises on it
- Cheating is also a way of denying yourself an opportunity of learning
- Would you advice your younger siblings, nephews, nieces, and your children to copy?
- If you still want to compromise on your integrity, don't even think of doing so in cs302 and cs316





IIT Bombay  
cs302: Implementation  
of Programming  
Languages

Topic:  
Compilation Overview

Section:

Outline

Introduction to  
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Modern Challenges

Incremental  
Construction of  
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Course Plan

Expectation  
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## Pre-empting Cheating

- cs302 exams will be designed in a manner that attending the lectures would be sufficient to pass them
- Getting high marks in two quizzes and mid-sem will guarantee passing even if you get a zero in the end-sem
- Getting full marks in first two assignments in cs316 will guarantee passing even if you do not submit the remaining assignments
- Your lab work will be in coffre VM
  - Flexibility of doing work at your convenience
  - Can be used on multiple devices
  - You are free to access internet while you work on your programming
  - All programming and submissions within coffre
  - No chance of taking any code into or out of the VM
  - All submissions will undergo through plagiarism checking
- Additional opportunities will be provided to students to pass the courses

Hopefully, I will make it harder for you to fail



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## Grade Litigation

- **Grade Litigation.** Requests for accepting incomplete or inaccurate answers, requests to condone errors in answers or implementations, seeking waivers motivated by improving chances of grades  
Persistent demands in the disguise of requests with a sense of entitlement
- **Grade litigation is easy to handle for small classes but not for large classes**
- My take motivated by consistency and reliability of grades in large classes
  - Marks are given for rigorous demonstration of knowledge *and* the skill of demonstrating the knowledge
  - Most students rely on knowledge but ignore the skill part and end up writing vague or incomplete answers
  - You cannot claim marks for indirectly showing that you possess the knowledge to solve a question You need to demonstrate it directly by showing
    - the skill of using the right knowledge, and
    - the diligence of solving the questions using the notations and conventions used in the class



# Grade Litigation

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- Practically, grade litigation in large classes amounts to a **Denial of Service Attack**  
Takes the time and energy away from
  - The students who need and deserve my time and attention
  - Improving my lectures, explanation, and course material
  - Designing interesting exams
- I do not take this denial of service attack, kindly



# Pre-empting The Grade Litigation for Large Classes: cs302

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- By design, the answers will be objective and precise and not subjective
- Answers will be subdivided into parts and there will be no partial marks other than the subdivision by parts
- All answers will be published and corrections, if any, as well as possible valid variations, will be invited before finalizing the marks
- Corrections and acceptable variations in the answers will be published and no requests for consideration of any other answers will be entertained
- Evaluated answer sheets will be made available for you to scan them and go through them at leisure to ensure that the evaluation is consistent with the published answers
- A grievance form will be floated and valid grievances will be addressed (no discussions over email/phone, please)



# Pre-empting The Grade Litigation for Large Classes: cs302

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Expectation  
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- A reference implementation of the compiler with test cases will be provided; you can run it on your own test cases to understand its behaviour
- You can submit the assignments late for reduced credit. Exact details will be provided in moodle.
- You will have a total four late days of submission without late penalty throughout the semester. You can use them for any assignment. Exact details will be provided on moodle
- Full grammar and class hierarchies used in the reference implementation will be provided; you are free to use your own grammar and classes but the output must match the output of the reference implementation
- The scripts and the test cases used for evaluation will be published
- A grievance form will be floated and valid grievances will be addressed (no discussions over email/phone, please)



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Compilation

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Compilation Models

Modern Challenges

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Compilers

Course Plan

Expectation  
Management

# Are you ready for the fun?