An Overview of Compilation

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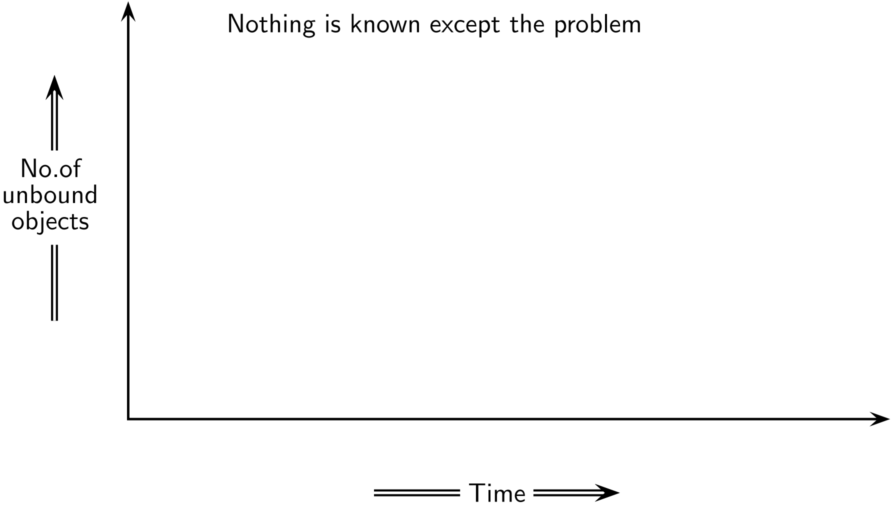
Outline

- Introduction
- Compilation phases
- Compilation models
- Incremental construction of compilers

Part 1

Introduction to Compilation

Binding

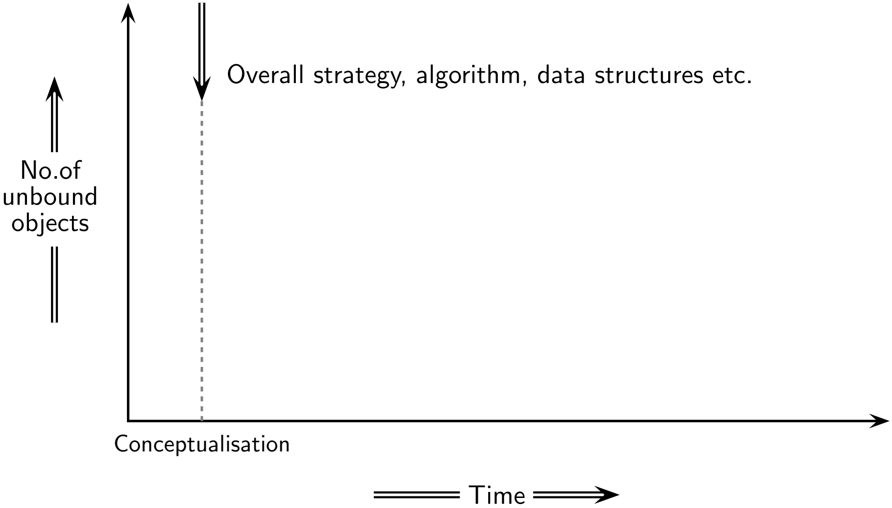


Nothing is known except the problem

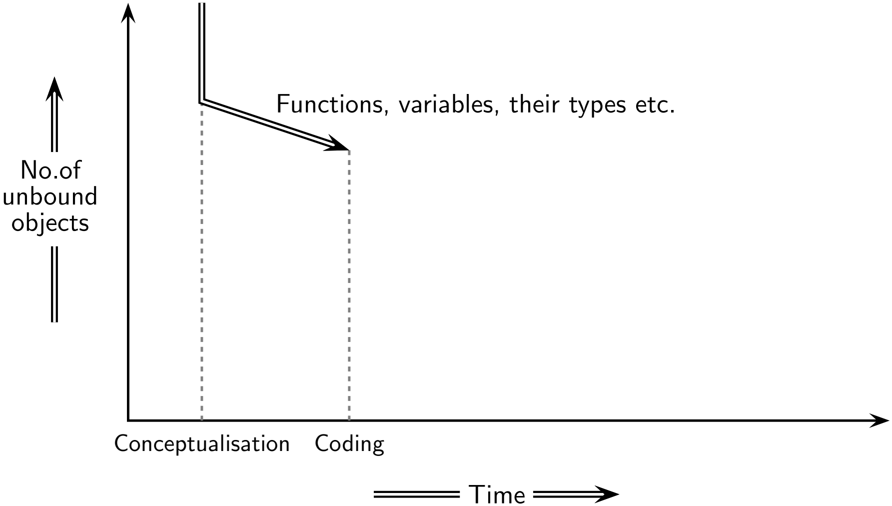
No.of unbound objects

Time

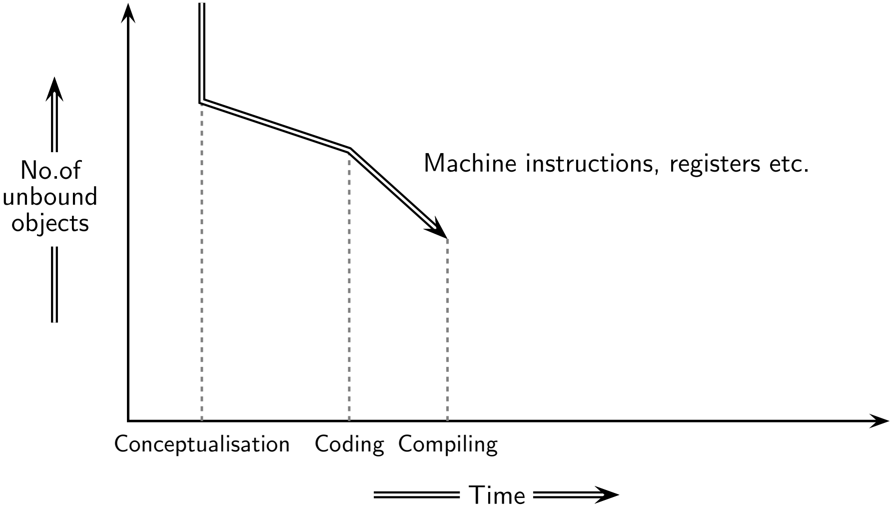
Binding


Overall strategy, algorithm, data structures etc.
No.of unbound objects
Conceptualisation
Time

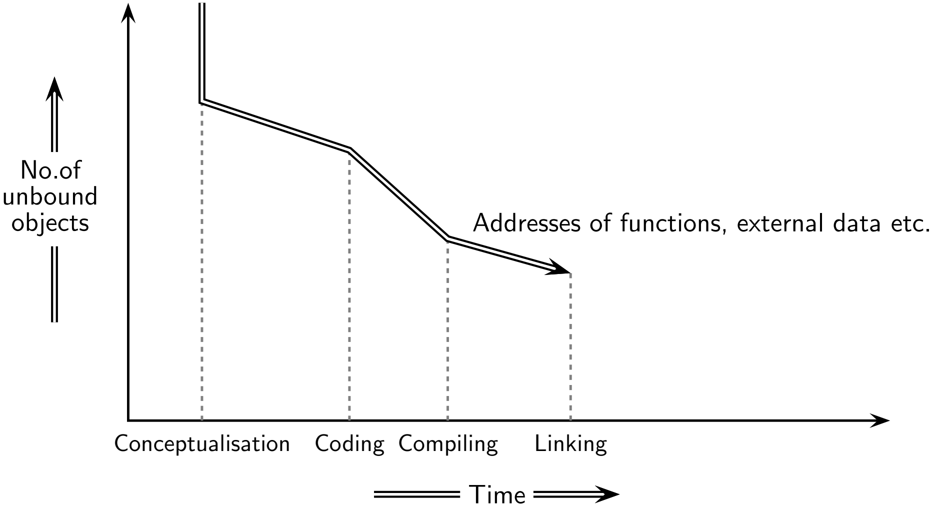
Binding


Functions, variables, their types etc.
No.of unbound objects
Conceptualisation
Coding
Time

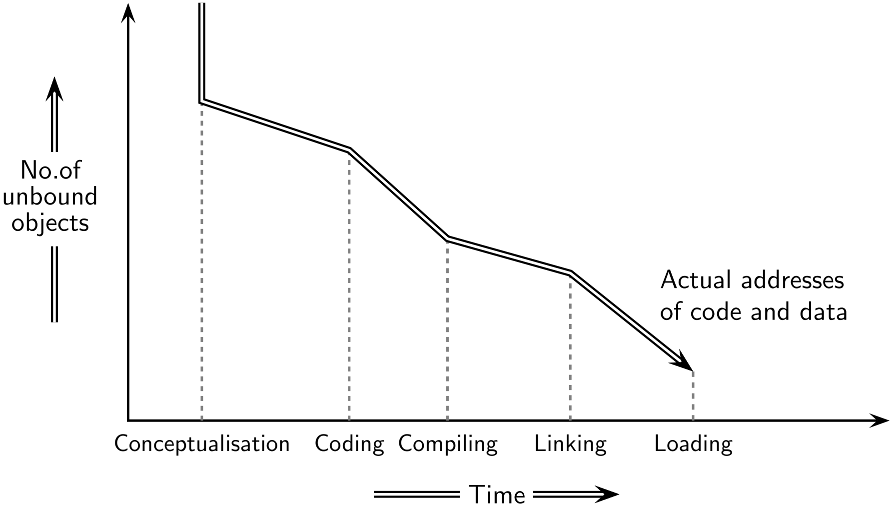
Binding


Machine instructions, registers etc.
No.of unbound objects
Conceptualisation
Coding
Compiling
Time

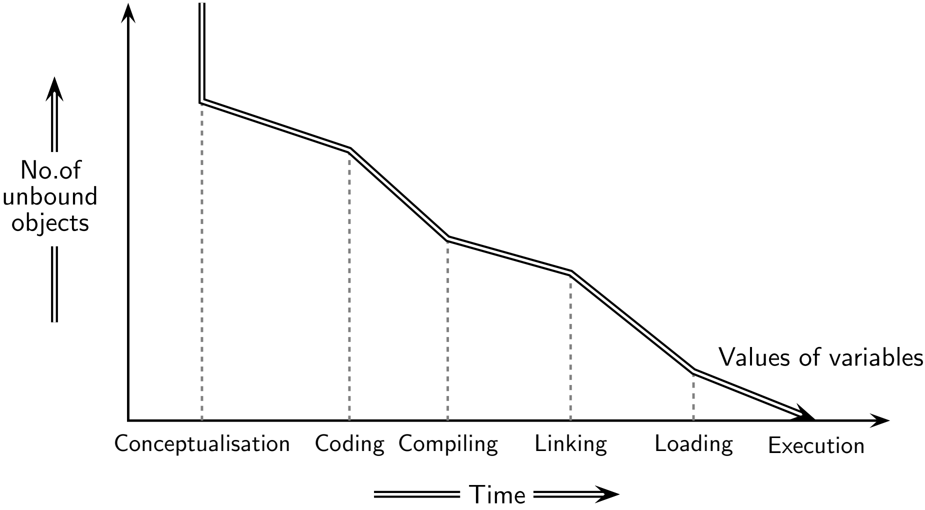
Binding


No.of unbound objects
Addresses of functions, external data etc.
Conceptualisation
Coding
Compiling
Linking
Time

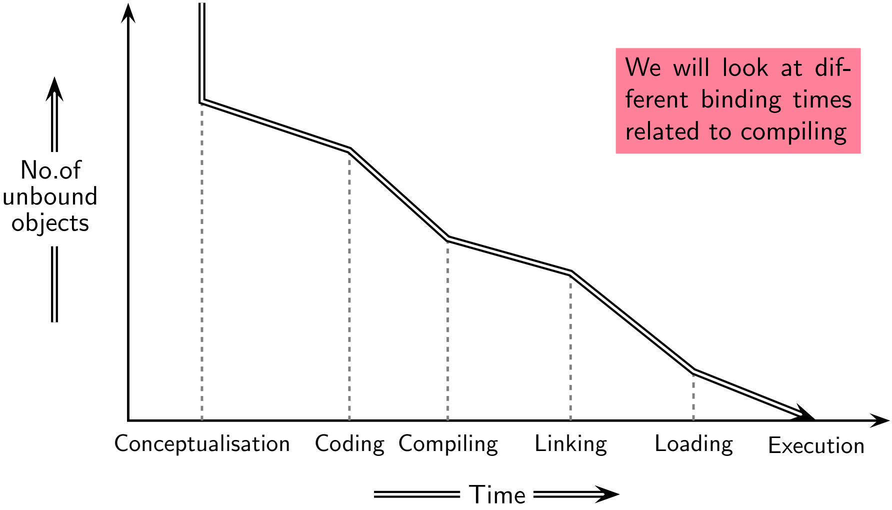
Binding


No.of unbound objects
Actual addresses of code and data
Conceptualisation
Coding
Compiling
Linking
Loading
Time

Binding

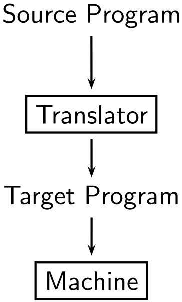

No.of unbound objects
Values of variables
Conceptualisation
Coding
Compiling
Linking
Loading
Execution
Time

Binding



We will look at different binding times related to compiling

Implementation Mechanisms

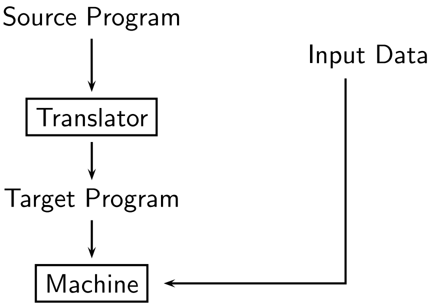

Source Program

Translator

Target Program

Machine

Implementation Mechanisms



Source Program

Translator

Target Program

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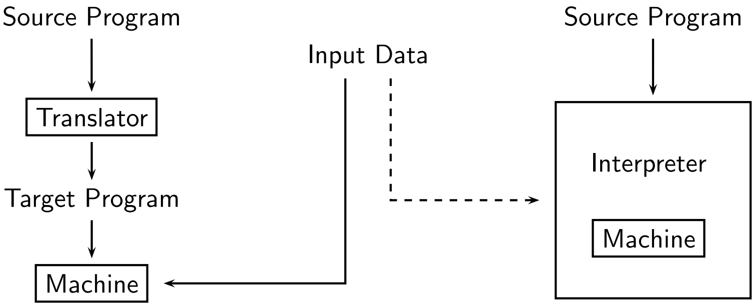
Input Data

Implementation Mechanisms



Source Program

Translator

Target Program

Machine

Input Data

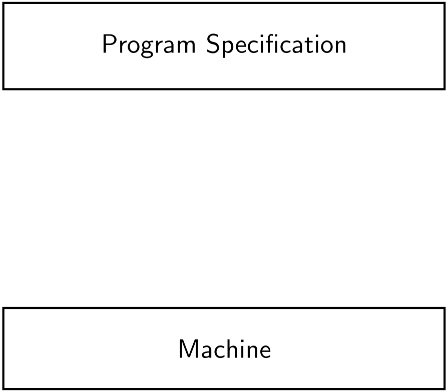
Source Program

Interpreter

Machine

Implementation Mechanisms as "Bridges"

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



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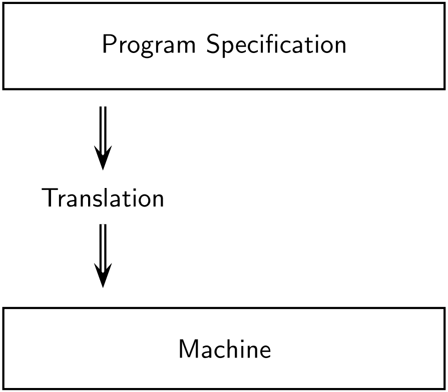


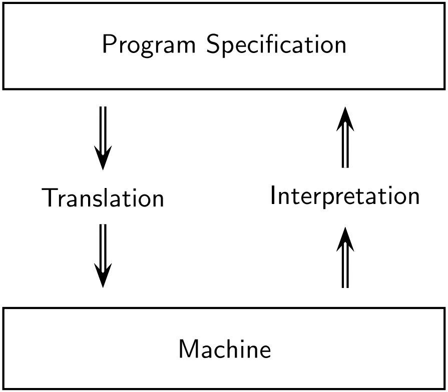
Program Specification

Translation

Machine

Implementation Mechanisms as "Bridges"

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


Program Specification

Translation

Interpretation

Machine

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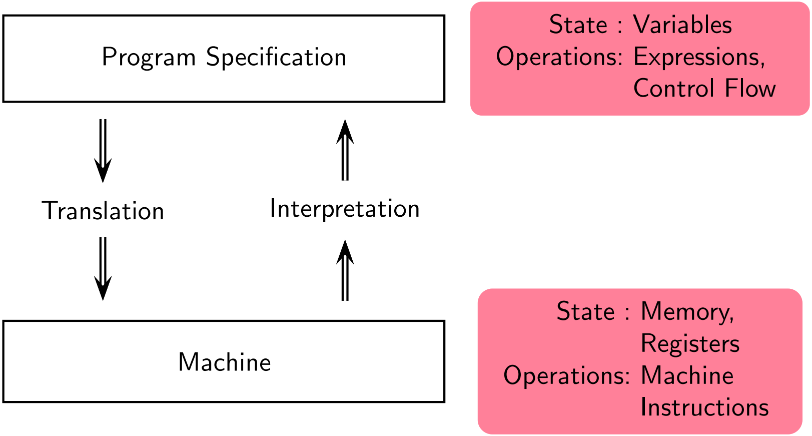

Program Specification

Translation

Interpretation

Machine

State : Variables
Operations: Expressions,
Control Flow

State : Memory,
Registers
Operations: Machine
Instructions

High and Low Level Abstractions

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 + c         # NO
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High and Low Level Abstractions

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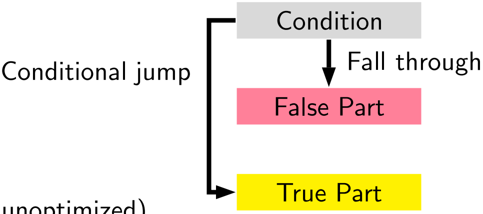

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High and Low Level Abstractions

NOT Condition

True Part

False Part

Input C statement

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Spim assembly equivalent (unoptimized)

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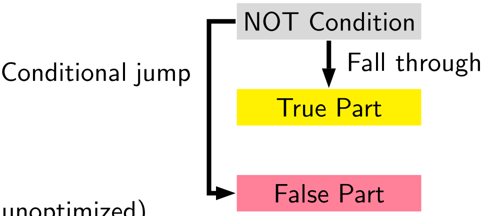
High and Low Level Abstractions


Conditional jump

NOT Condition

Fall through

True Part

False Part

Input C statement

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Implementation Mechanisms

- Translation = Analysis + Synthesis
  Interpretation = Analysis + Execution

Implementation Mechanisms

- $$\begin{aligned}\text{Translation} &= \text{Analysis} + \text{Synthesis}\\ \text{Interpretation} &= \text{Analysis} + \text{Execution}\end{aligned}$$

- Translation Instructions $\Longrightarrow$ Equivalent Instructions

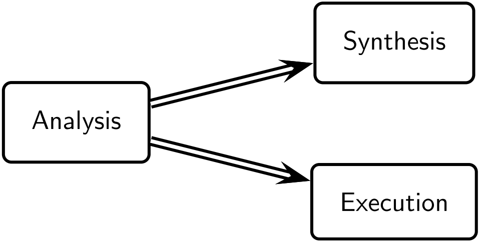
Implementation Mechanisms

- Translation = Analysis + Synthesis
  Interpretation = Analysis + Execution

- Translation Instructions $\Longrightarrow$ Equivalent Instructions

  Interpretation Instructions $\Longrightarrow$ Actions Implied by Instructions

Language Implementation Models



Analysis

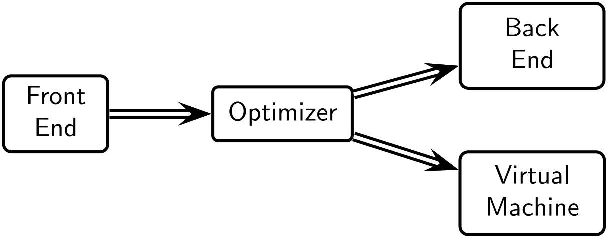
Synthesis

Execution

Compilation

Interpretation

Language Processor Models



C,C++

Java, C#

Part 2

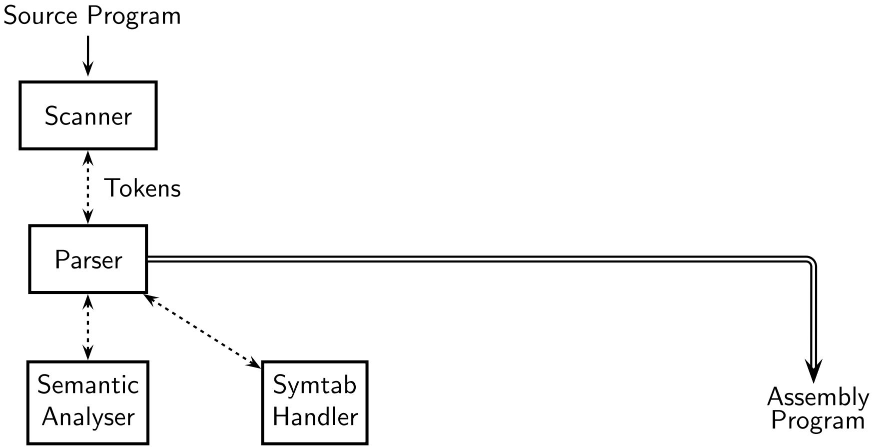
An Overview of Compilation Phases

The Structure of a Simple Compiler

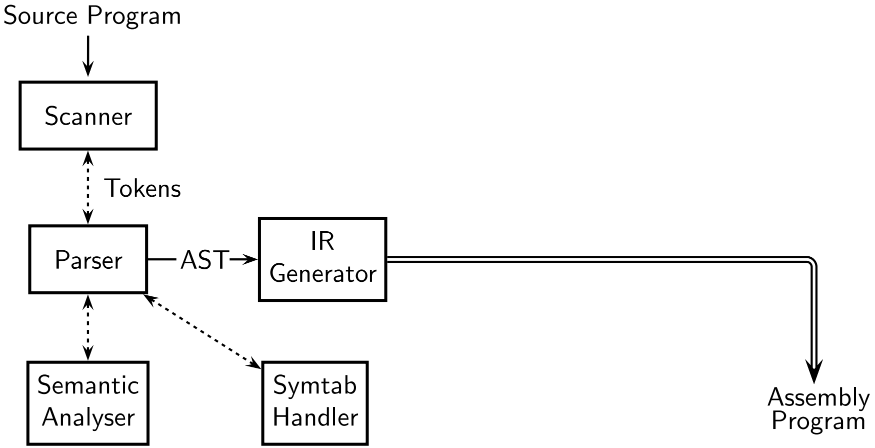

Source Program

Assembly Program

The Structure of a Simple Compiler



The Structure of a Simple Compiler


Source Program

Scanner

Tokens

Parser

AST

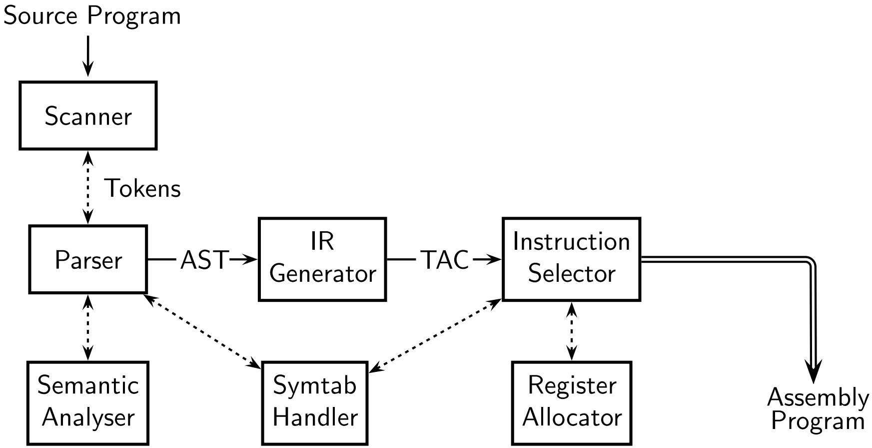
IR Generator

Semantic Analyser

Symtab Handler

Assembly Program

The Structure of a Simple Compiler



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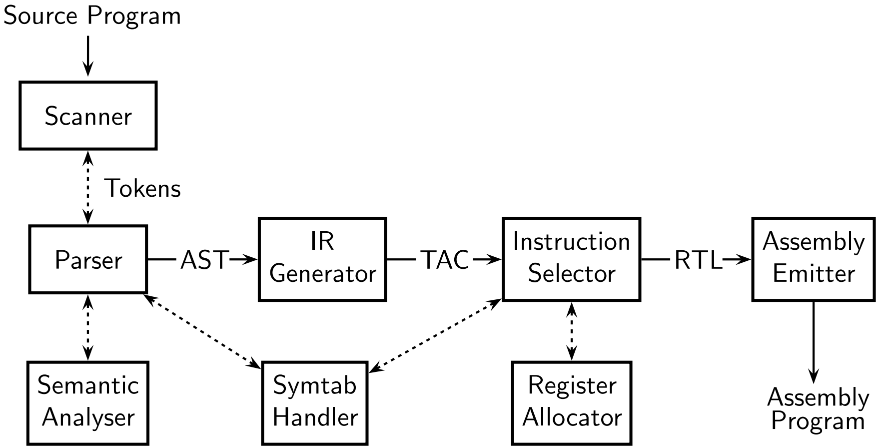
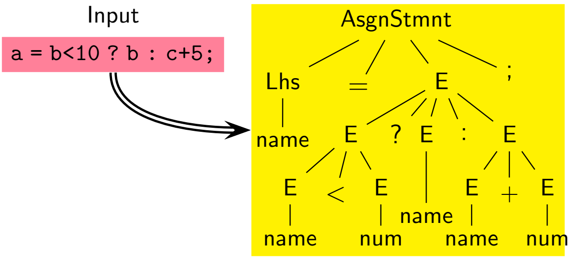


Translation Sequence in Our Compiler: Scanning and Parsing

Input

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

Translation Sequence in Our Compiler: Scanning and Parsing



Parse Tree

How the input is actually stored in the memory

`a␣=␣b␣<␣10␣?␣b␣:␣c␣+␣5␣;␣`

How we want to see it

$\boxed{\texttt{a}}␣\boxed{\texttt{=}}␣\boxed{\texttt{b}}␣\boxed{\texttt{<}}␣\boxed{\texttt{10}}␣\boxed{\texttt{?}}␣\boxed{\texttt{b}}␣\boxed{\texttt{:}}␣\boxed{\texttt{c}}␣\boxed{\texttt{+}}␣\boxed{\texttt{5}}␣\boxed{\texttt{;}}␣$

Issues:

- Grammar rules, terminals, non-terminals
- Order of application of grammar rules

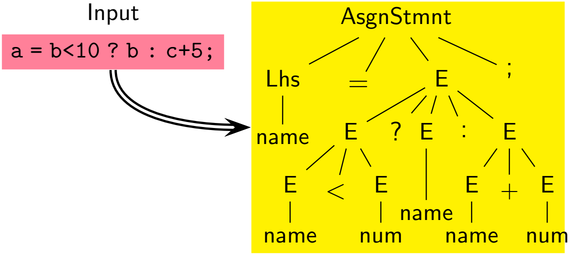
  eg. is it (`a = b<10?`) followed by (`b:c`)?
- Values of terminal symbols

  eg. string "10" vs. integer number 10.

Translation Sequence in Our Compiler: Semantic Analysis

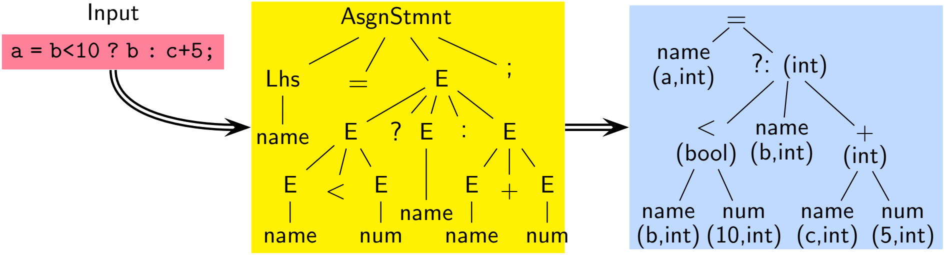
Input

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



Parse Tree

Translation Sequence in Our Compiler: Semantic Analysis



Parse Tree

Abstract Syntax Tree
(with attributes)

Issues:

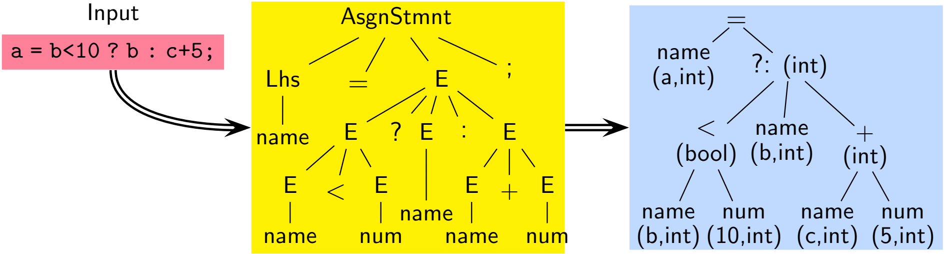
- Symbol tables

  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

Translation Sequence in Our Compiler: IR Generation



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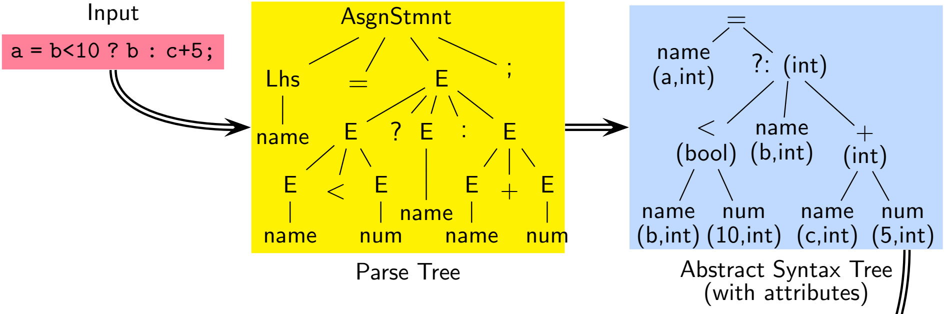

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TAC List

$T_1 = b < 10$
$T_2 = \neg T_1$
if T_2 goto L0
$T_3 = b$
goto L1:
L0: $T_3 = c + 5$
L1: $a = T_3$

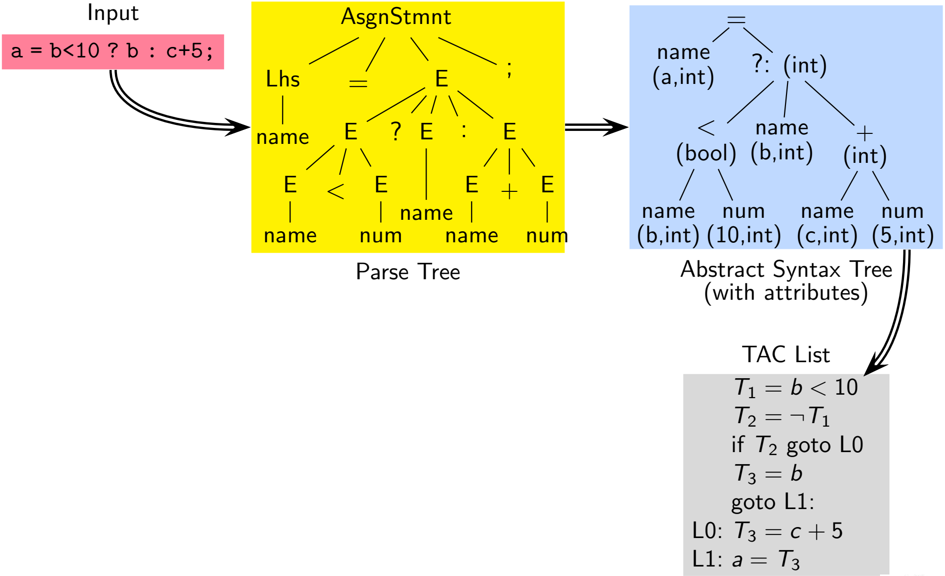
Issues:

- Convert to three address code (TAC) separating data and control flow

  Simplifies optimization

- Linearise control flow by flattening nested control constructs

Translation Sequence in Our Compiler: Instruction Selection



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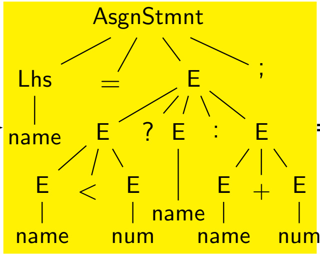

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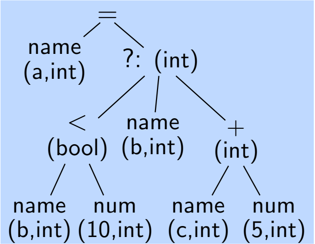

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RTL List

load $v0 \leftarrow b$
slti $t1 \leftarrow v0, 10$
not $t2 \leftarrow t1$
if $t2$ goto L0
load $t3 \leftarrow b$
goto L1
L0: load $t4 \leftarrow c$
addi $t3 \leftarrow t4, 5$
L1: store $a \leftarrow t3$

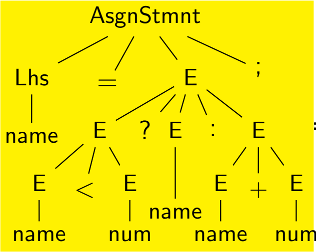
Issues:

- Generate as few instructions as possible (list shown here is unoptimized)
- Use temporaries and local registers

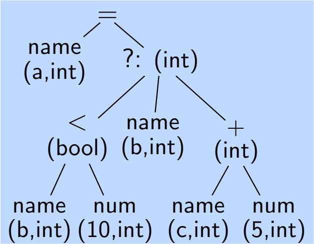
Translation Sequence in Our Compiler: Emitting Instructions

Input

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



Parse Tree



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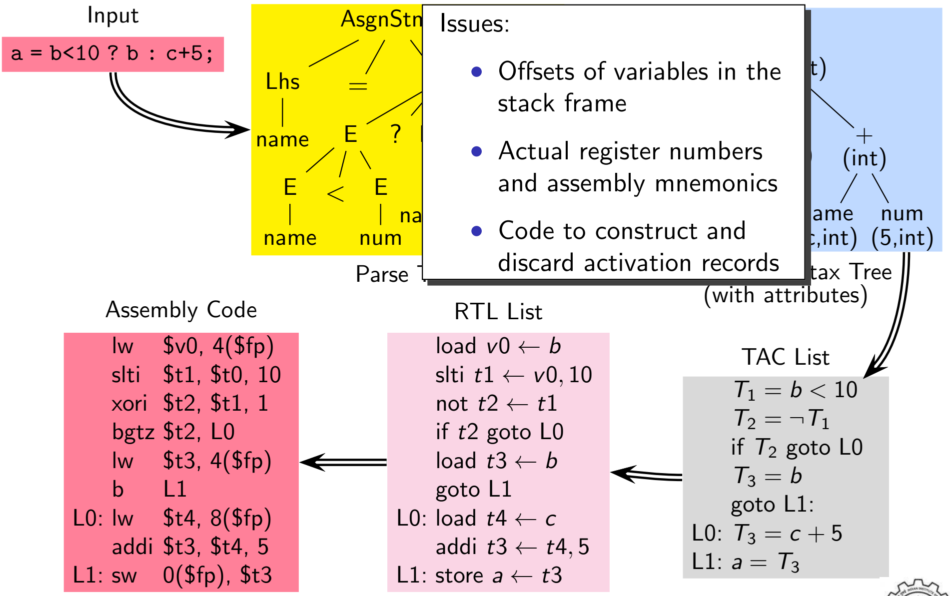

Input

```
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```

Issues:

- Offsets of variables in the stack frame
- Actual register numbers and assembly mnemonics
- Code to construct and discard activation records

TAC List

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Assembly Code

```
    lw   $v0, 4($fp)
    slti $t1, $t0, 10
    xori $t2, $t1, 1
    bgtz $t2, L0
    lw   $t3, 4($fp)
    b    L1
L0: lw   $t4, 8($fp)
    addi $t3, $t4, 5
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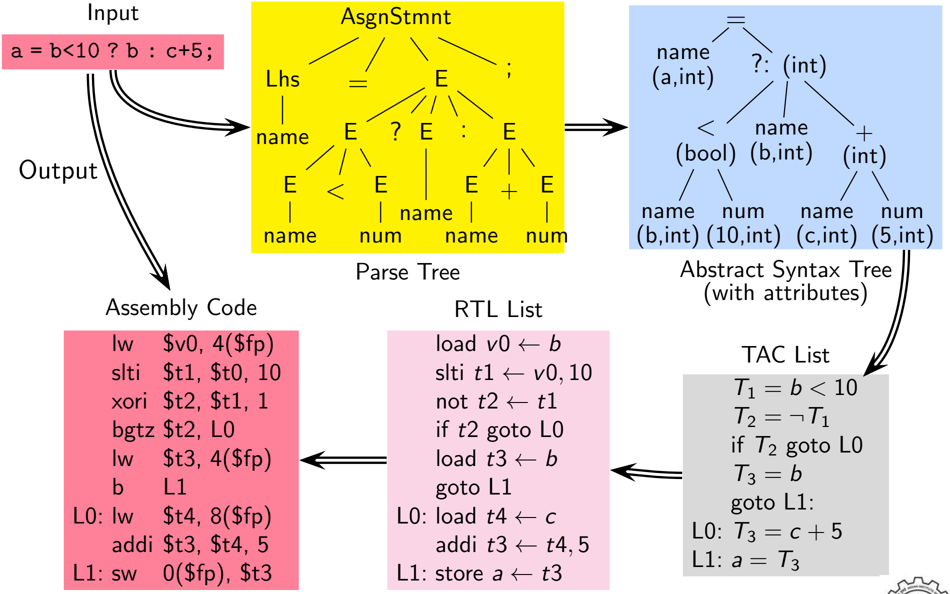
Translation Sequence in Our Compiler: Emitting Instructions



Input

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Output

Parse Tree

Abstract Syntax Tree (with attributes)

Assembly Code

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RTL List

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    - How many IRs should we have?
    - What are the details that each IR captures?

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- 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?
- Practical compilers are desired to be retargetable
  ⇒ Back ends should be generated from specifications

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Very few people write compilers any way

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    - Stepwise refinement Vs. look up
    - Analytics Vs. Transactional software

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- Computer Science is all about building abstractions and bridging abstraction gaps

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- Translation and interpretation are fundamental CS at a conceptual level
  - Stepwise refinement Vs. look up
  - Analytics Vs. Transactional software
- Computer Science is all about building abstractions and bridging abstraction gaps
- Knowing compilers internals makes a person a much better programmer
  Writing programs whose data is programs

Part 3

Compilation Models

Compilation Models

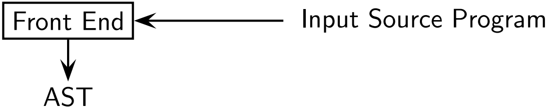
Aho Ullman Model

Davidson Fraser Model

Compilation Models

Aho Ullman Model

Davidson Fraser Model



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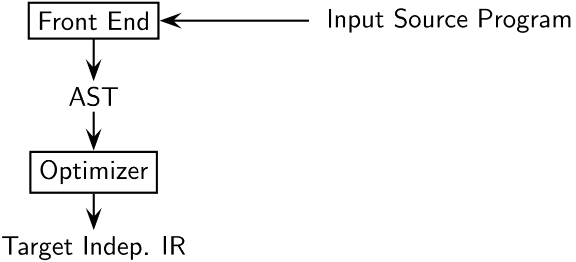


Front End

Input Source Program

AST

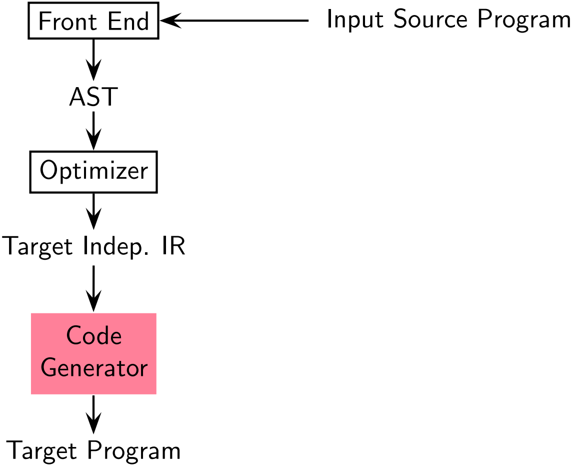
Optimizer

Target Indep. IR

Compilation Models

Aho Ullman Model

Davidson Fraser Model



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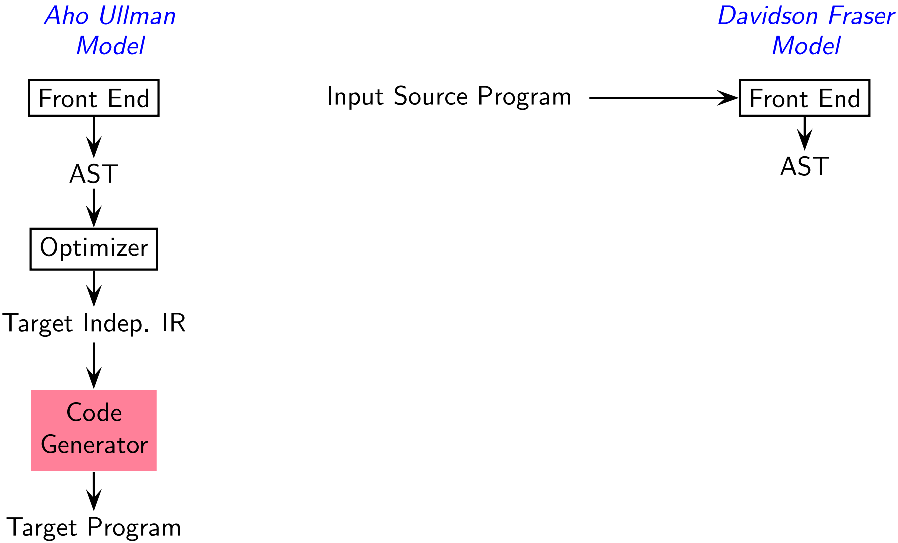

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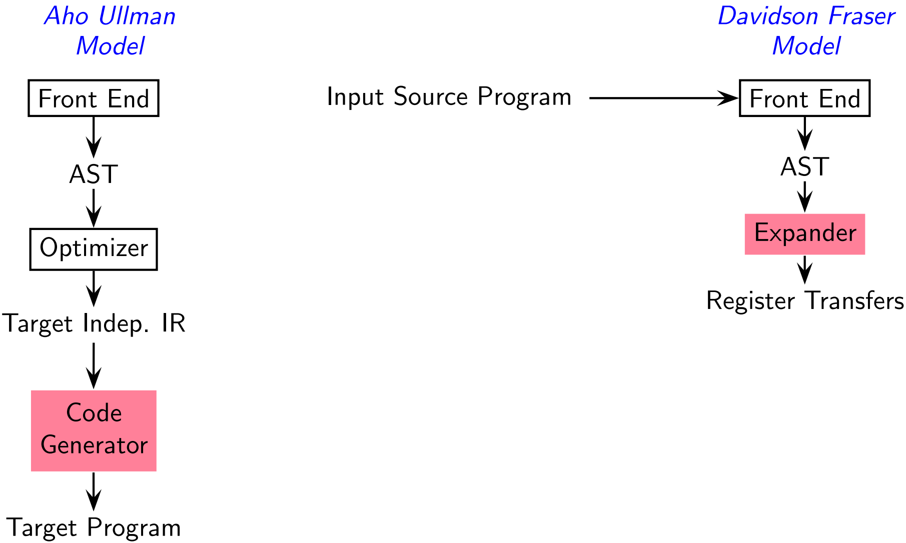

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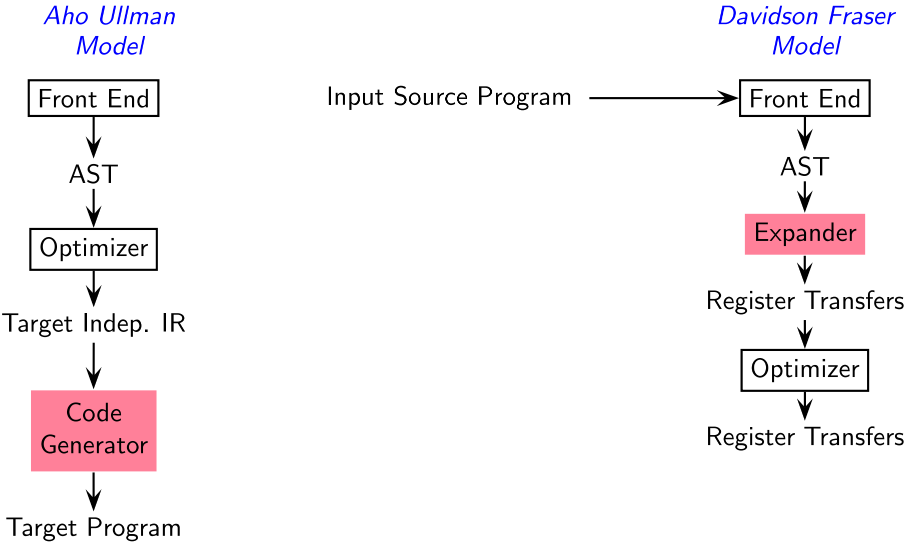

Aho Ullman Model

Front End

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Optimizer

Target Indep. IR

Code Generator

Target Program

Input Source Program

Davidson Fraser Model

Front End

AST

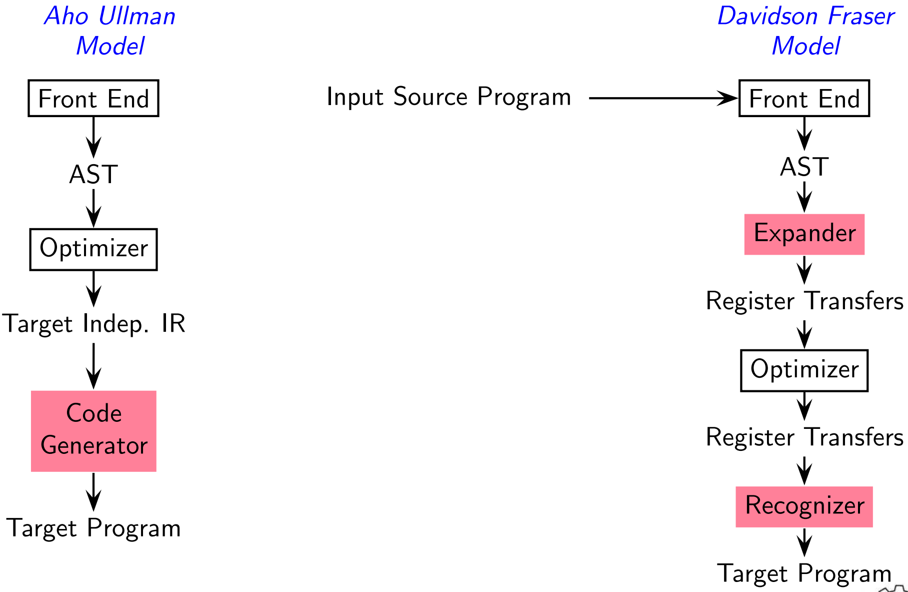
Expander

Register Transfers

Optimizer

Register Transfers

Compilation Models



Aho Ullman Model

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Expander

Register Transfers

Optimizer

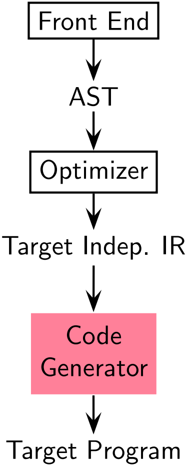
Register Transfers

Recognizer

Target Program

Compilation Models

Aho Ullman Model



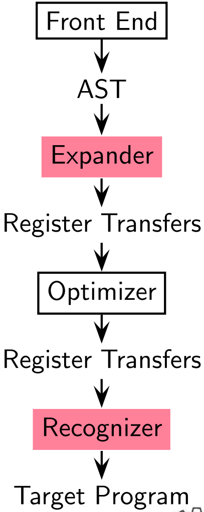
Aho Ullman: Instruction selection

- 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

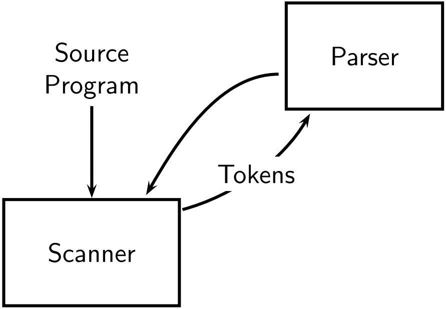
Davidson Fraser Model



Typical Front Ends

Parser

Typical Front Ends



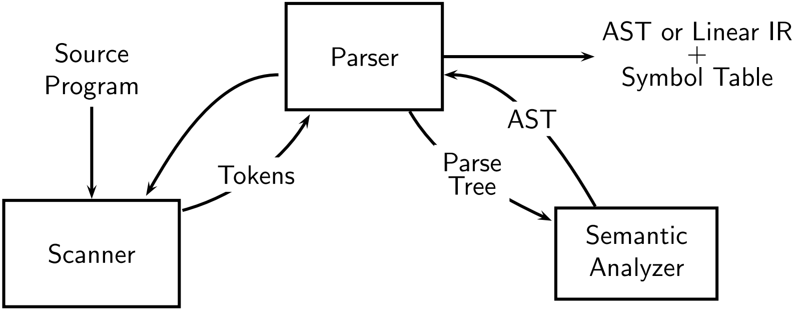
Source Program

Parser

Tokens

Scanner

Typical Front Ends



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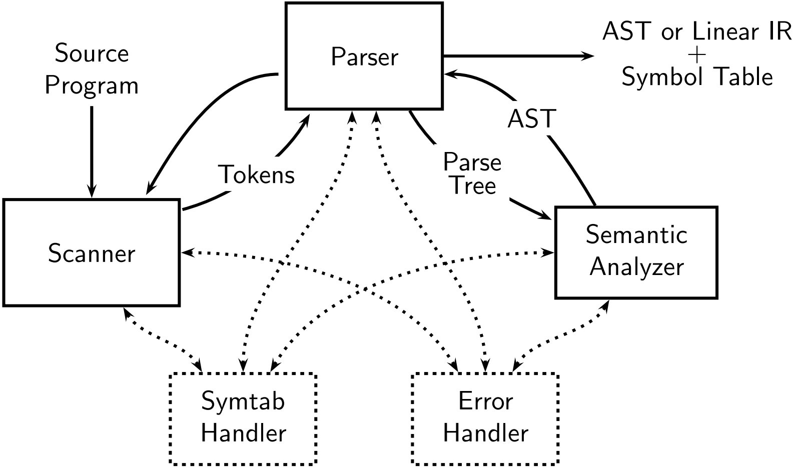
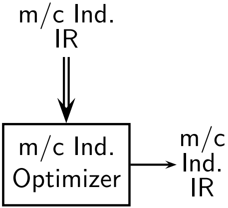
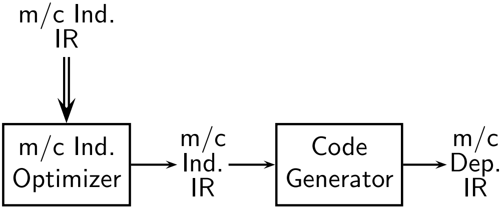


Typical Back Ends in Aho Ullman Model



- Compile time evaluations
- Eliminating redundant computations

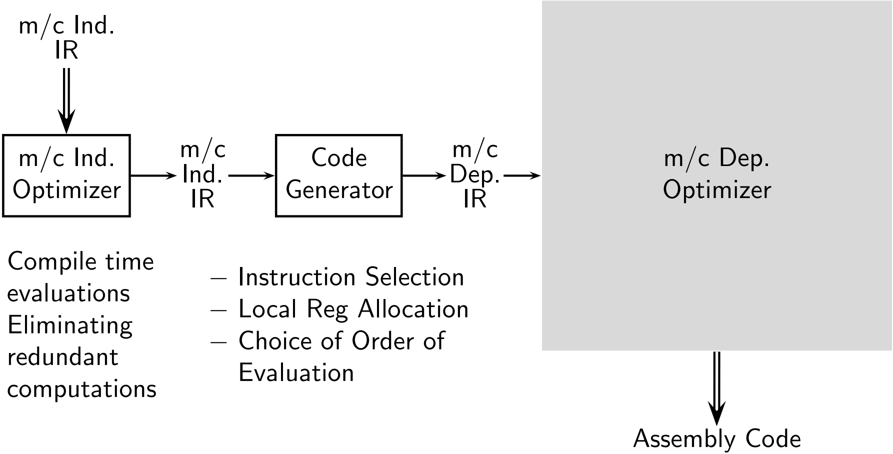
Typical Back Ends in Aho Ullman Model



- Compile time evaluations
- Eliminating redundant computations

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

Typical Back Ends in Aho Ullman Model



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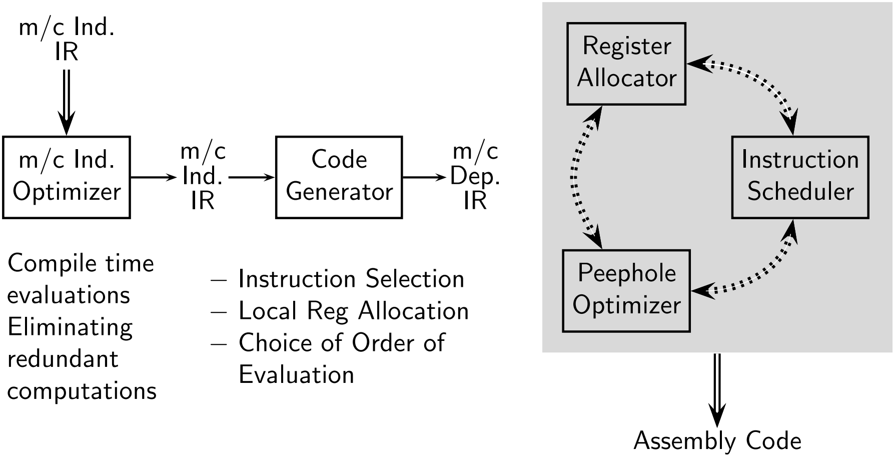

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Retargetability in Aho Ullman and Davidson Fraser Models

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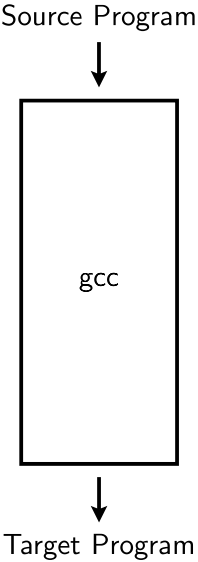
Instruction Selection	• Machine independent IR is expressed in the form of trees • Machine instructions are described in the form of trees • Trees in the IR are "covered" using the instruction trees	
	Cost based tree pattern matching	Structural tree pattern matching
Optimization	Machine independent	Machine dependent
		Key Insight: *Register transfers are target specific but their form is target independent*

The GNU Tool Chain for C

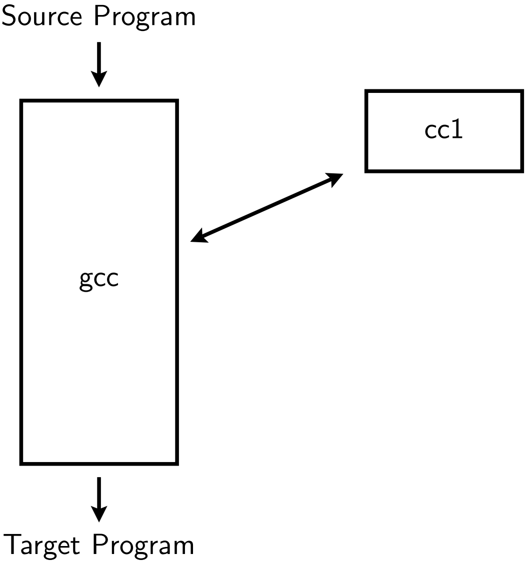


Source Program

gcc

Target Program

The GNU Tool Chain for C



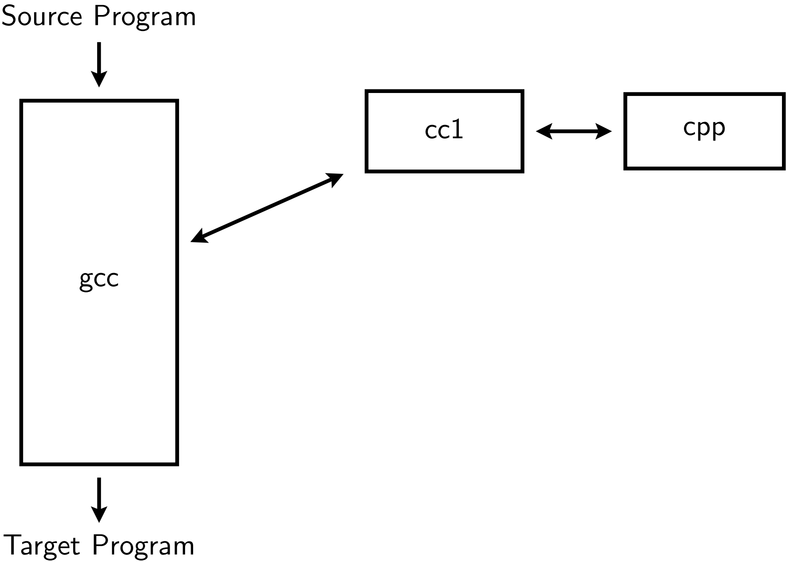
Source Program

gcc

cc1

Target Program

The GNU Tool Chain for C



Source Program

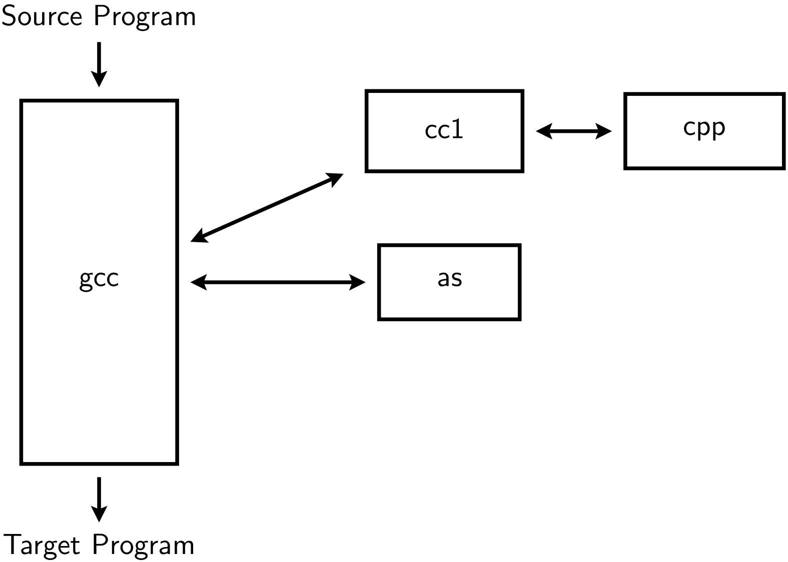
gcc

cc1

cpp

Target Program

The GNU Tool Chain for C



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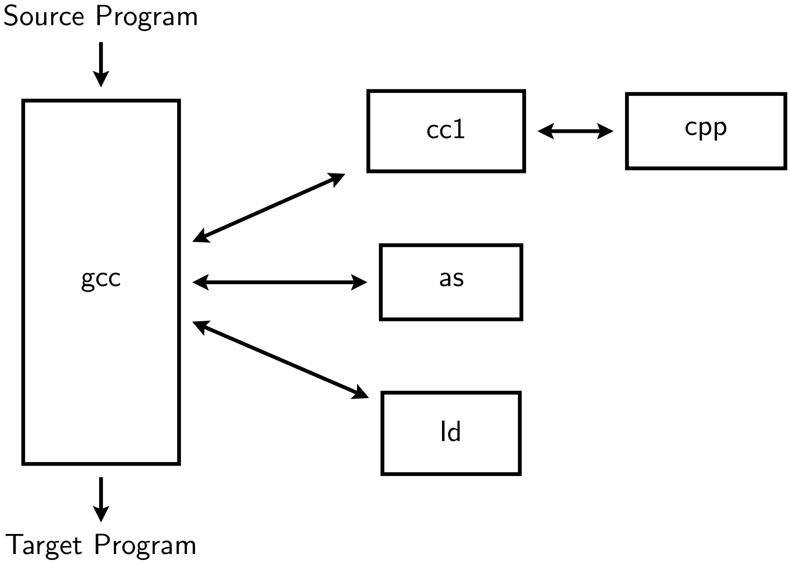


Source Program

gcc

cc1

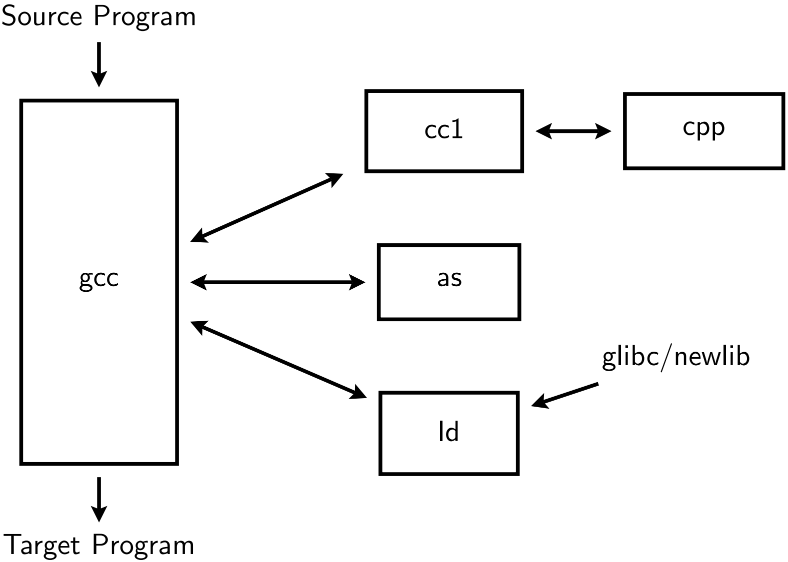
cpp

as

ld

Target Program

The GNU Tool Chain for C



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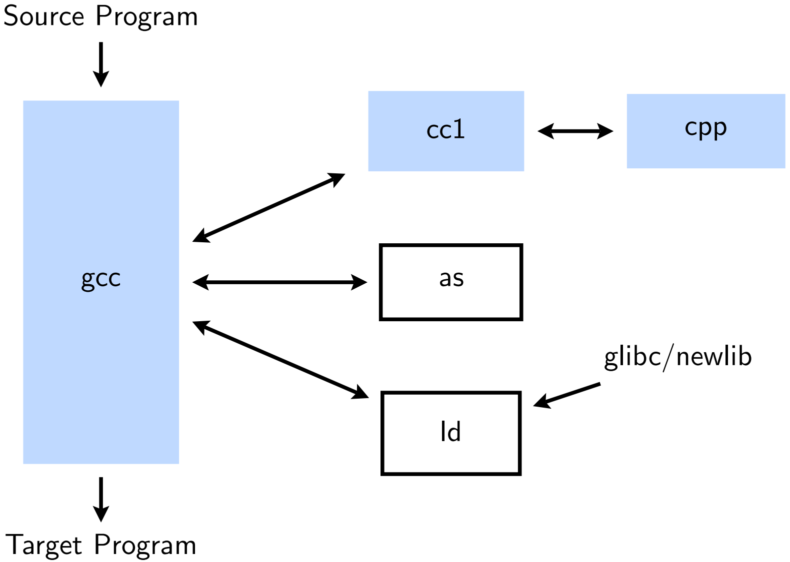


Source Program

gcc

cc1

cpp

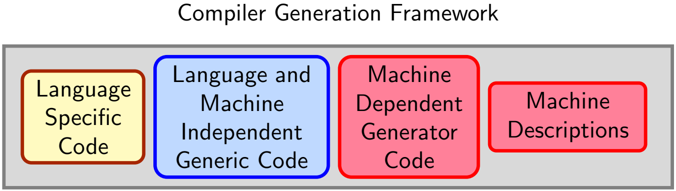
as

ld

glibc/newlib

Target Program

The Architecture of GCC



Compiler Generation Framework

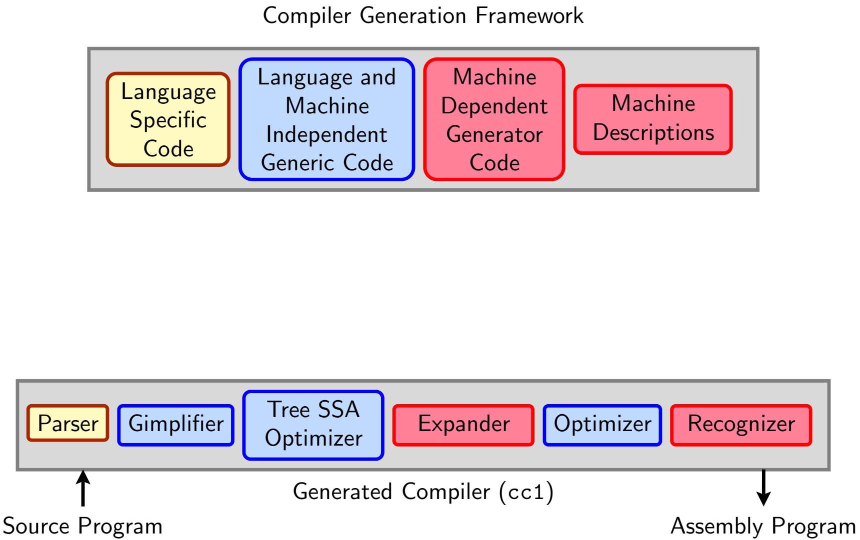
Language Specific Code

Language and Machine Independent Generic Code

Machine Dependent Generator Code

Machine Descriptions

The Architecture of GCC



Compiler Generation Framework

Language Specific Code

Language and Machine Independent Generic Code

Machine Dependent Generator Code

Machine Descriptions

Parser

Gimplifier

Tree SSA Optimizer

Expander

Optimizer

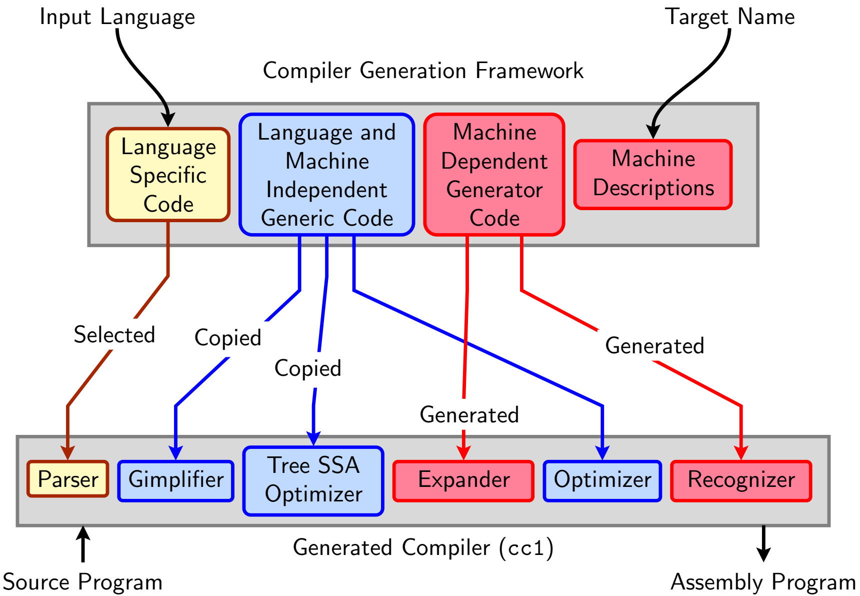
Recognizer

Generated Compiler (cc1)

Source Program

Assembly Program

The Architecture of GCC



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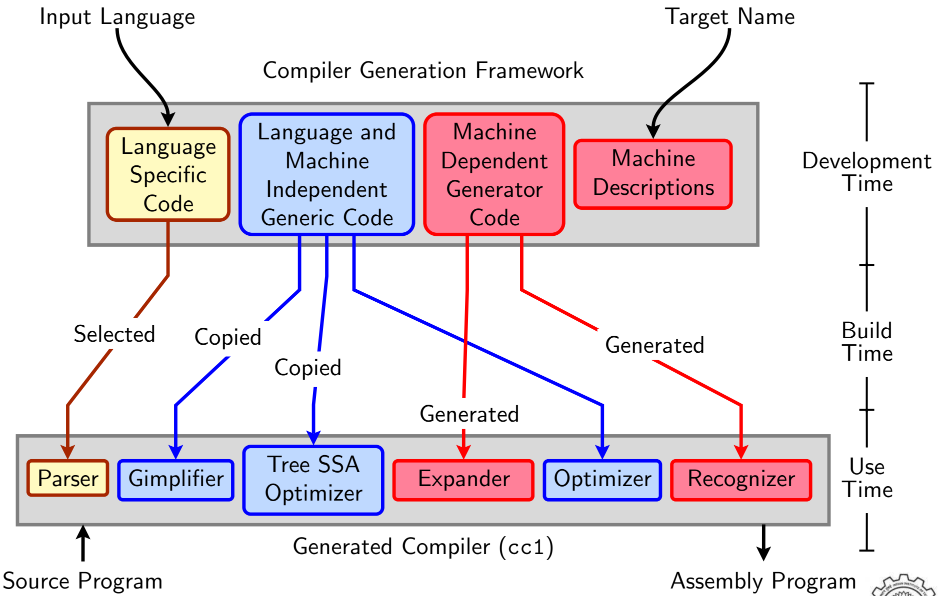
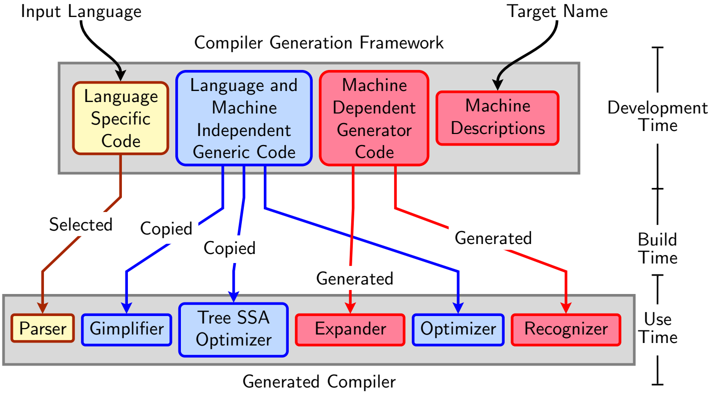


GCC Retargetability Mechanism



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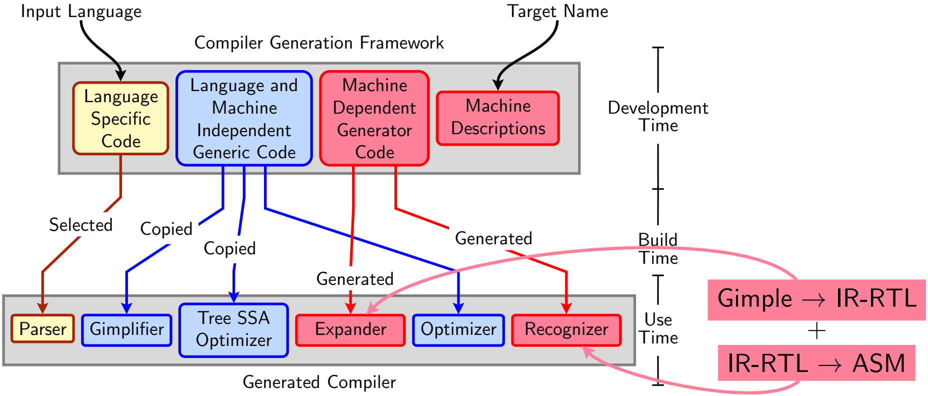

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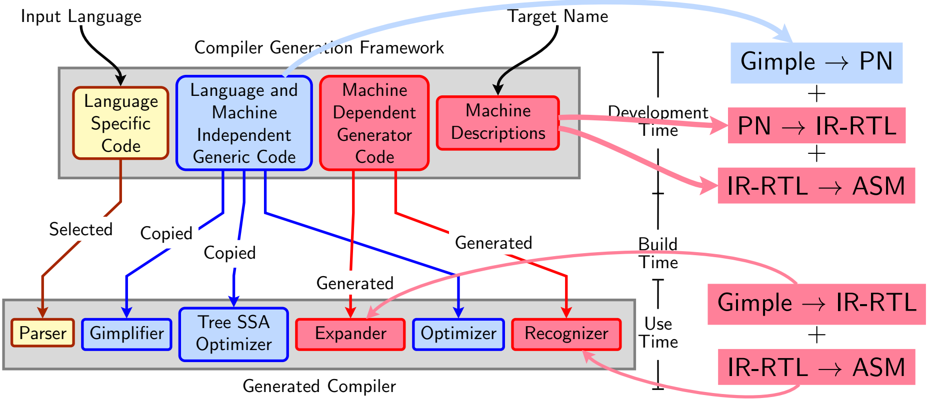

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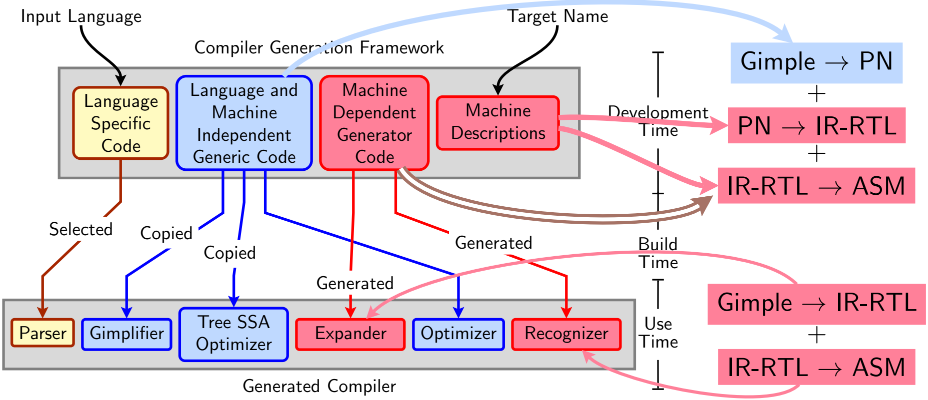

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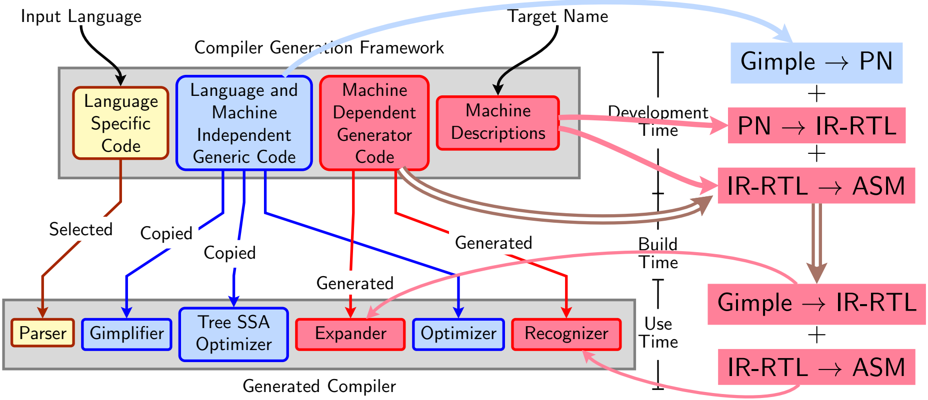

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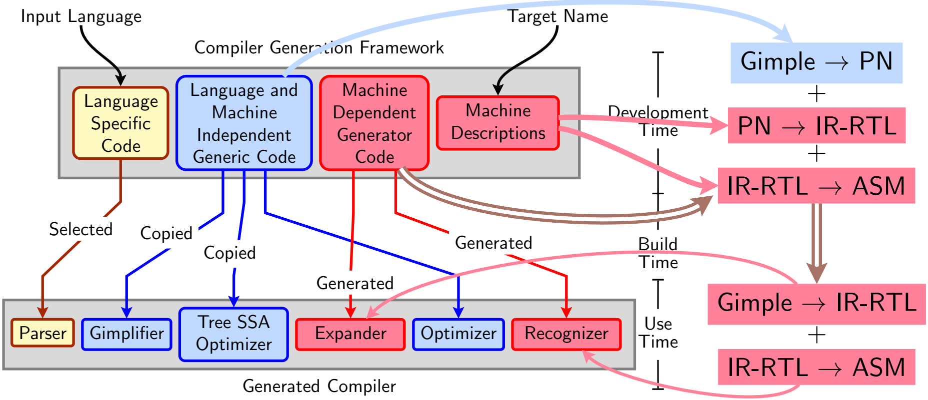

The generated compiler uses an adaptation of the Davidson Fraser model

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

Part 4

Modern Challenges

The Sources of New Challenges

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

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

Modern Challenges: Design issues

- The IR interface

  What to export? What to hide?
- Retargetability

  Extending to the new version of a processor?

  Extending to a new processor?

Modern Challenges: Improving Program

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

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

Modern Challenges: Target Machine Issues

How to exploit

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

Modern Challenges: Target Machine Issues

How to exploit

- Pipelines? (Spectre bug)

The crux of the matter

- Hardware is parallel, (conventional) software is sequential
- Software view of memory model: Strong consistency
  Architecture gives weak consistency
- Software view is stable, hardware is disruptive

Modern Challenges: Providing Guarantees

- Correctness of optimizations
    - Hard even for machine independent optimizations
    - Verification of a production optimizing compiler is a pipe dream
      Requires roving 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

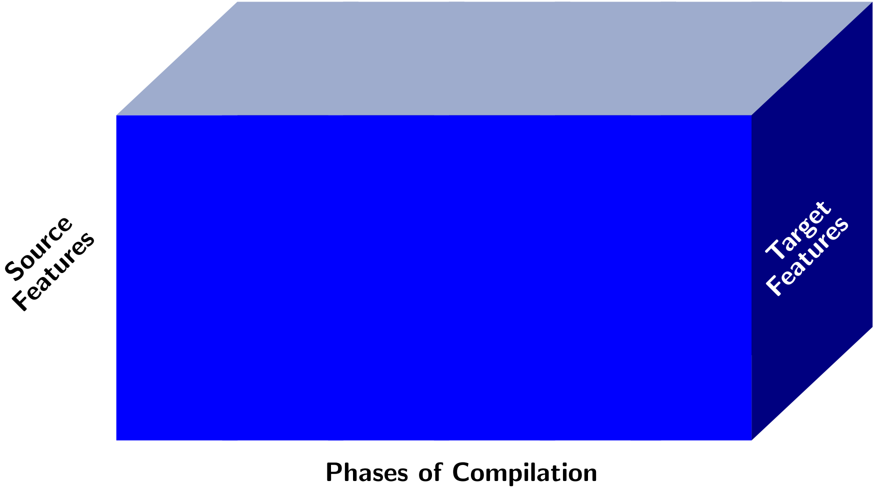
Modern Challenges: New Expectations

- 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?
  - Langueg 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?
  - Can compilers learn from the programs they have compiled and become “better” over time?

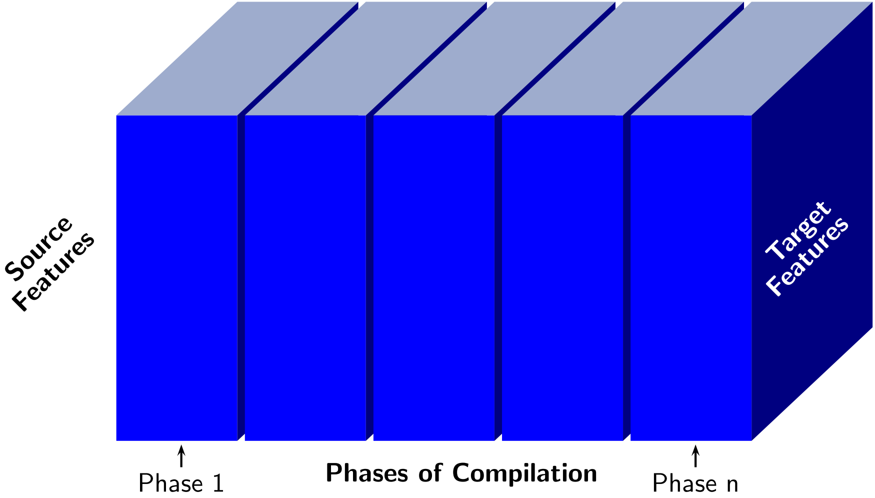
Part 5

Incremental Construction of Compilers

In Search of Modularity in Compilation



In Search of Modularity in Compilation



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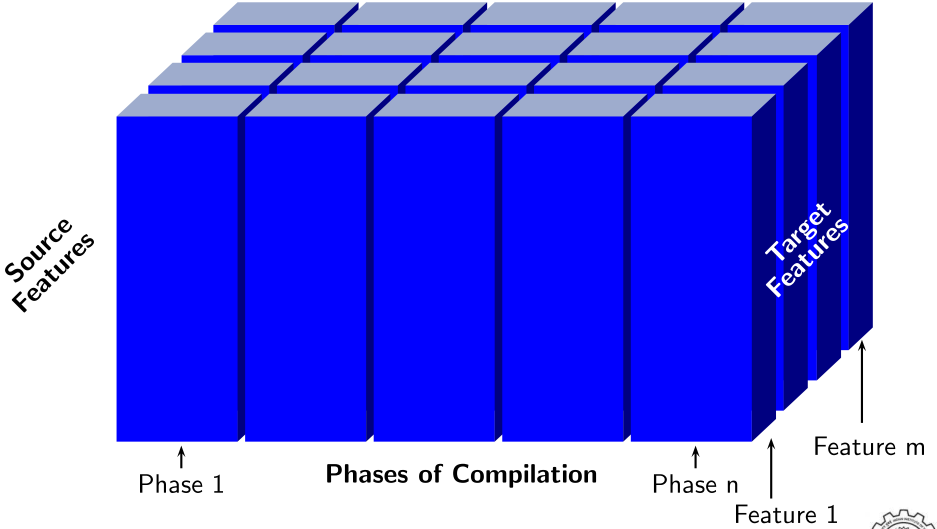
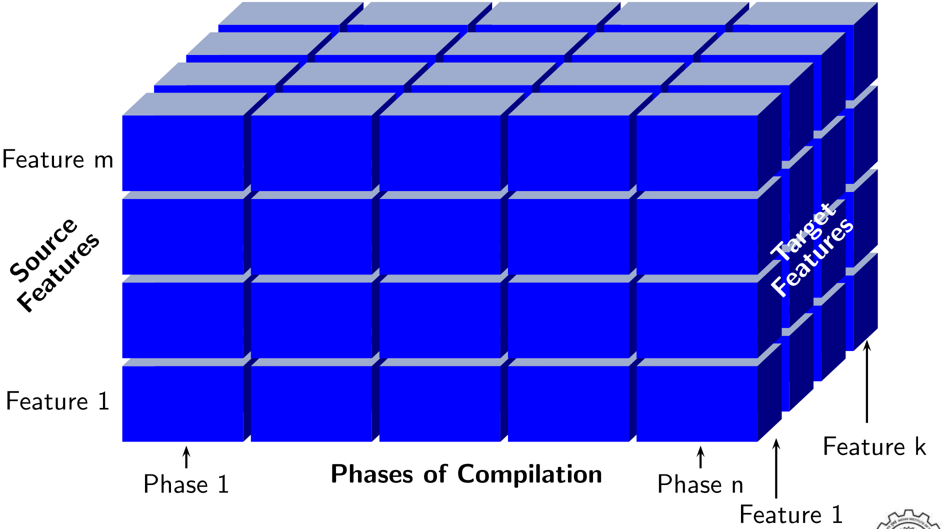


In Search of Modularity in Retargetable Compilation



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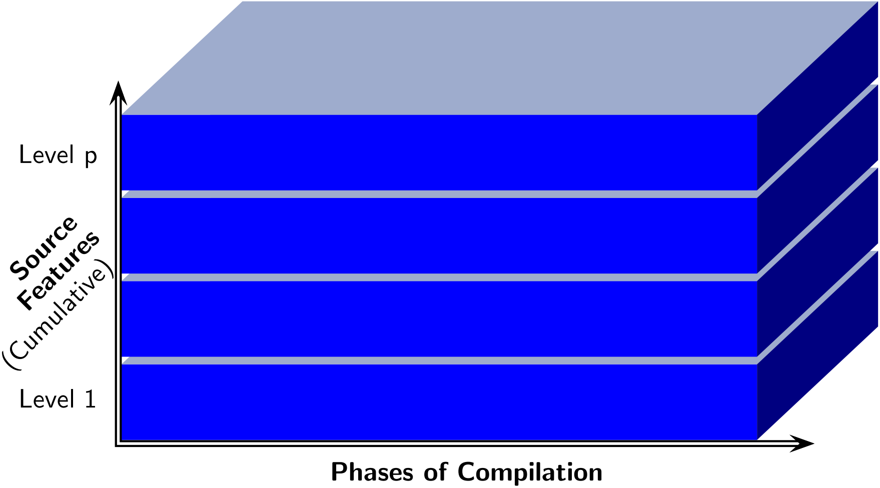
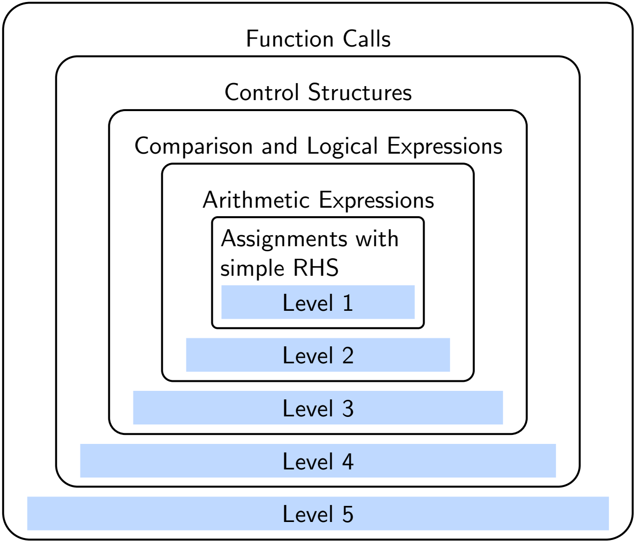


Language Increments



Function Calls

Control Structures

Comparison and Logical Expressions

Arithmetic Expressions

Assignments with simple RHS

Level 1

Level 2

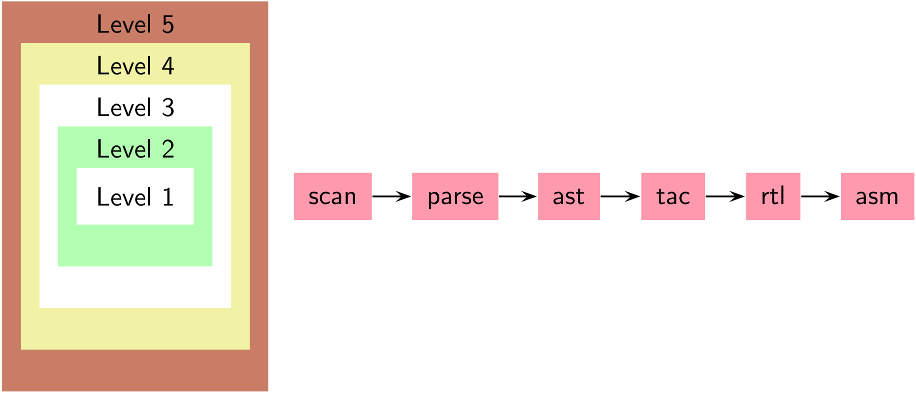
Level 3

Level 4

Level 5

Proposed Assignment Plan

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



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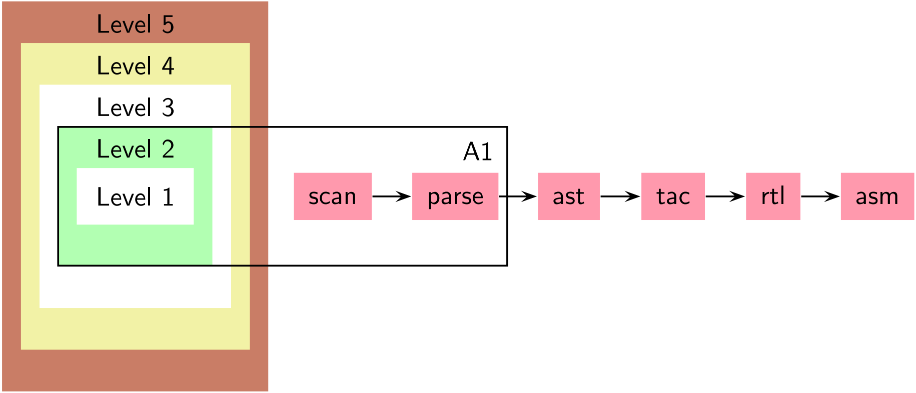

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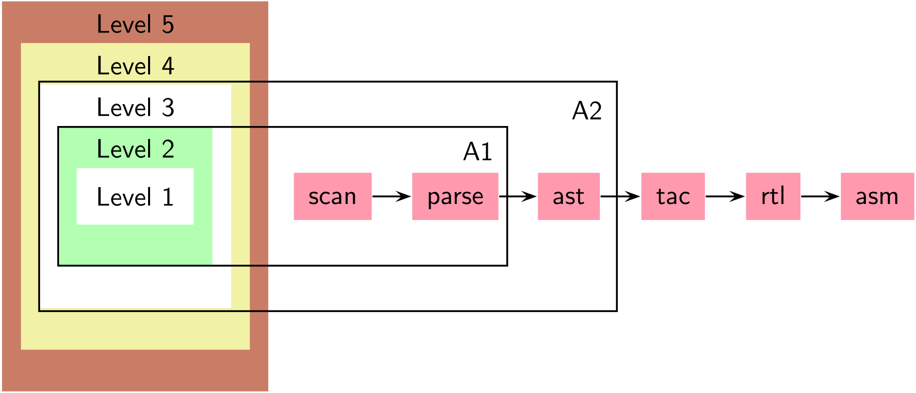

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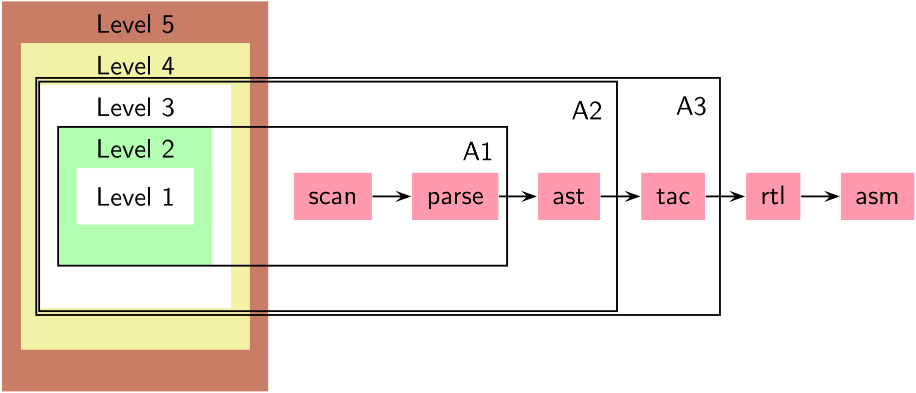

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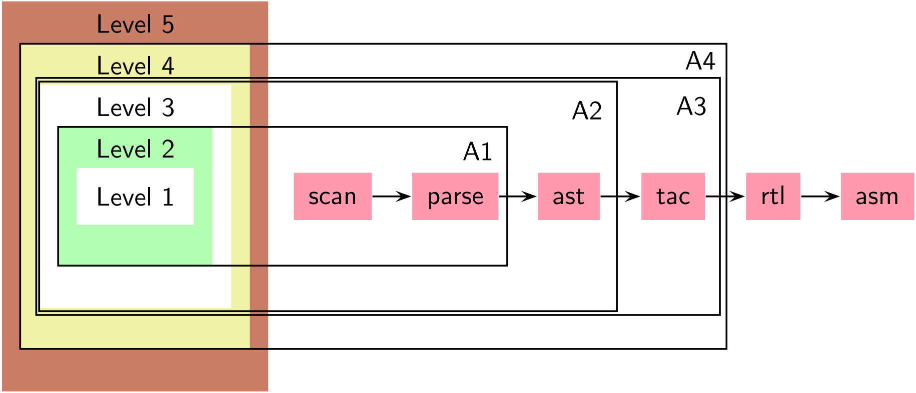

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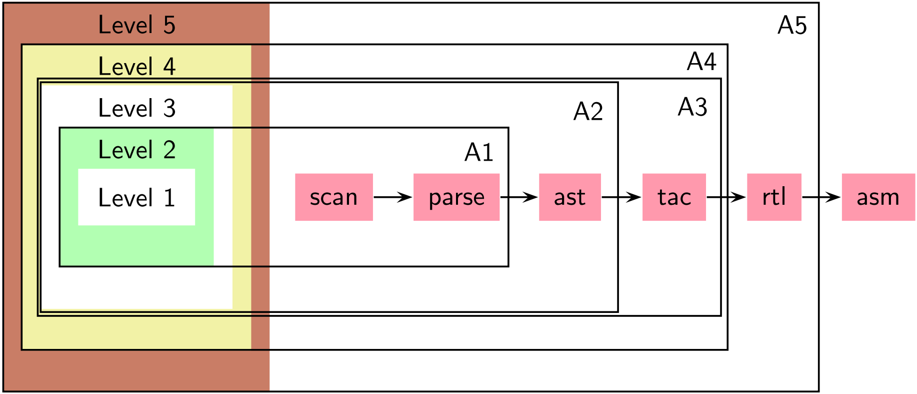

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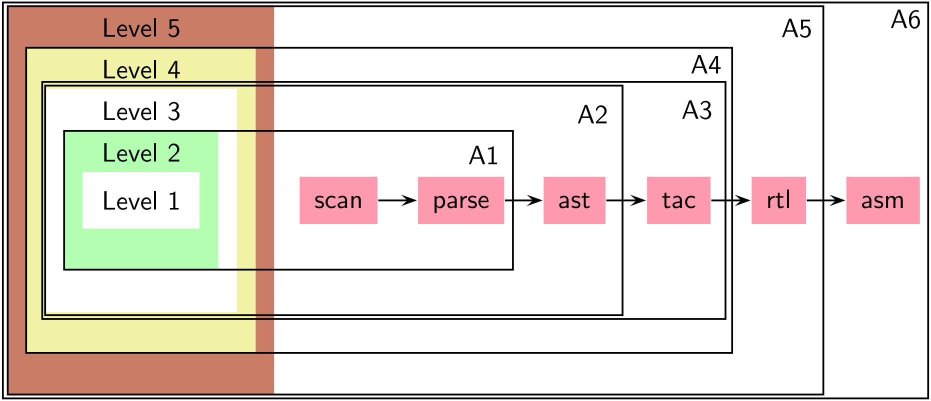

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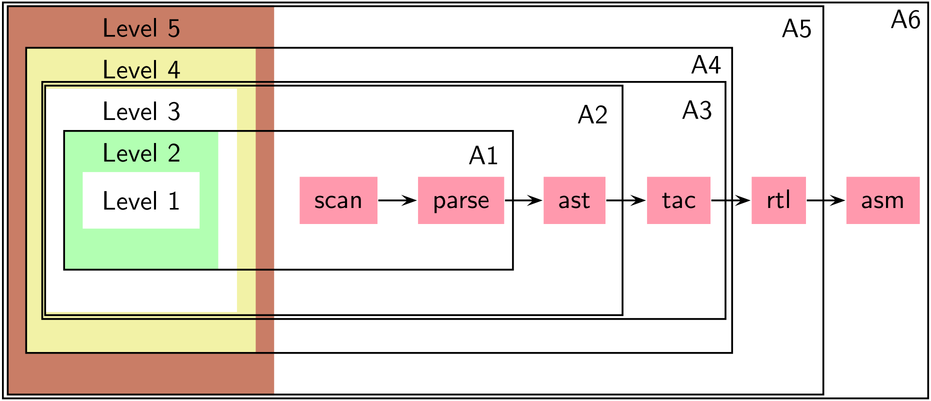

Further details will be provided in the lab session