Review

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COMP 3002

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What is a Compiler

- A compiler translates
  - from a source language S
  - to a target language T
  - while preserving the meaning of the input

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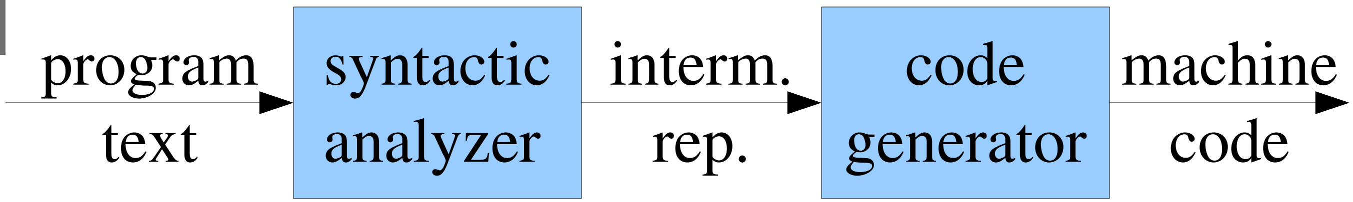
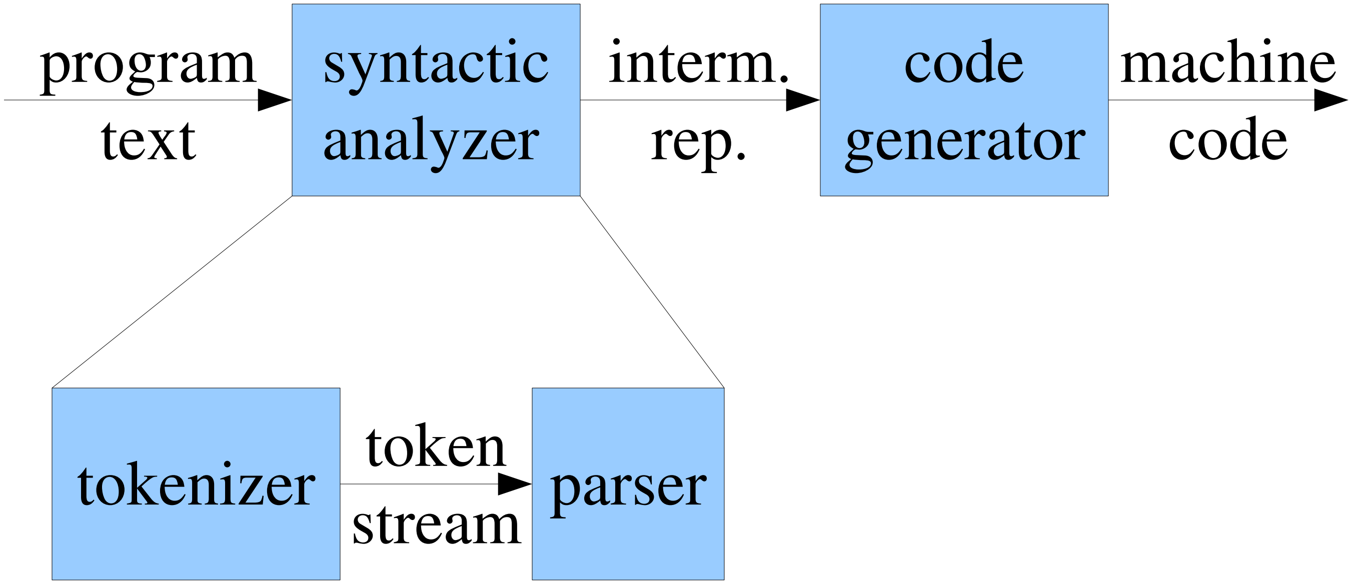
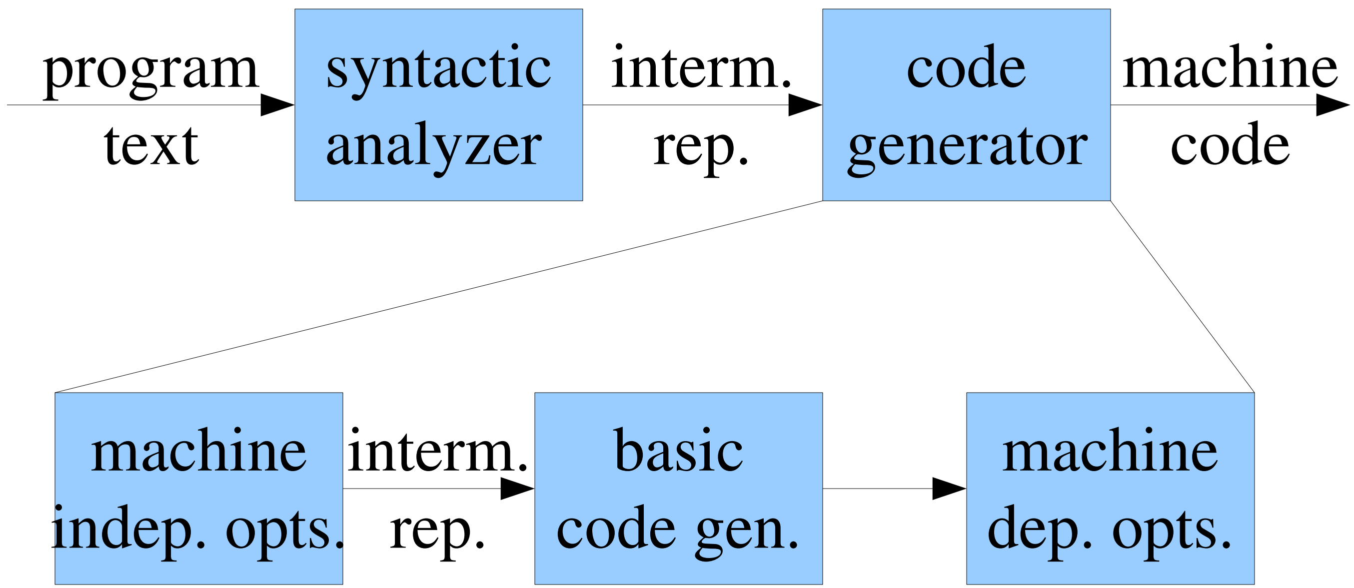
Structure of a Compiler



Compiler Structure: Front End



Compiler Structure: Back End



Tokenizing

- The first step in compilation
  - takes the input (a character stream) and converts it into a token stream
  - Tokens have attributes
- Technology
  - Convert regular expressions into
  - NFA and then convert into
  - DFA

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Regular Expressions

- Concatenation, alternation, Kleene closure, and parenthesization
- Regular definitions
  - multiline regular expressions
- **Exercise:** Write regular definitions for
  - All strings of lowercase letters that contain the five vowels in order
  - All strings of lowercase letters in which the letters are in ascending lexicographic order
  - Comments, consisting of a string surrounded by /* and */ without any intervening */

NFAs

- Finite collection of states
- Edges are labelled with letters
- One start state
- (Wlog) one accepting state
- **Exercise:** Convert these to NFA
  - a|b
  - (a|b)c
  - (a|b)*c
  - (a|b)* a (a|b)(a|b)

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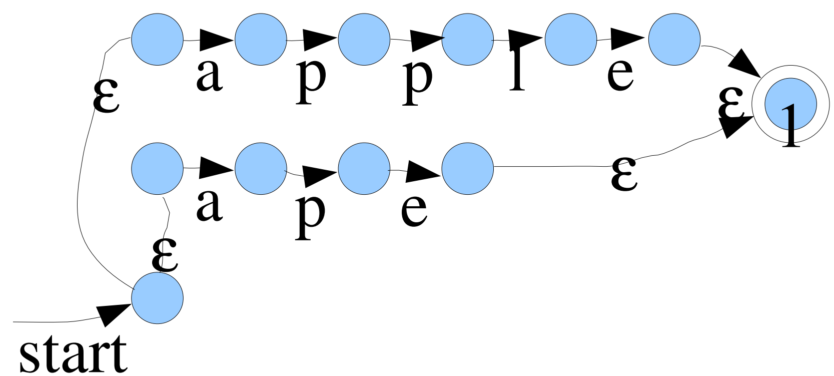
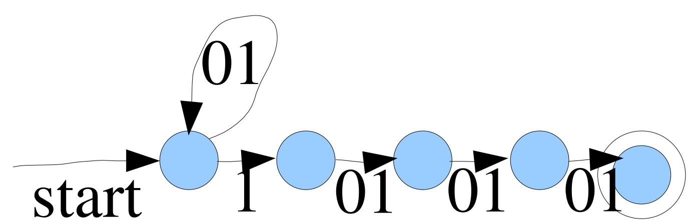
DFAs

- Like NFAs, but
  - all the outgoing edges of any node have distinct labels
- Any NFA can be converted to an equivalent DFA
- **Exercises:**
  - Convert to DFA:



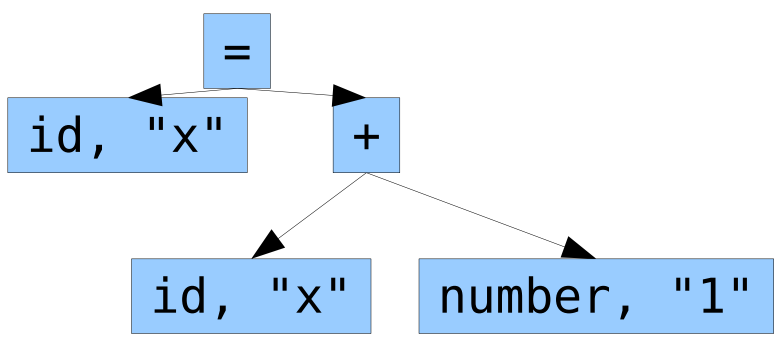


Parsing

- Purpose
  - Convert a token stream into a parse tree

```
x = x + 1
```

```
<id, "x"> <assign> <id, "x"> <plus> <number, "1">
```



Context-Free Grammars

- Context-free grammars have
  - terminals (tokens)
  - non-terminals
  - sentential forms
  - sentences
- Derivations
  - Derive `id + id * id` with this grammar:

$$
\begin{aligned}
E &\rightarrow E + T \mid T \\
T &\rightarrow T * F \mid F \\
F &\rightarrow (E) \mid \textbf{id}
\end{aligned}
$$

Derivations

- Leftmost (rightmost) derivations
  – Always expand the leftmost (rightmost) non-terminal
- Derivations and parse trees
  – Internal nodes correspond to non-terminals
  – Leaves correspond to terminal
- Ambiguity
  – When a string has more than one derivation
  – Can result in different parse trees

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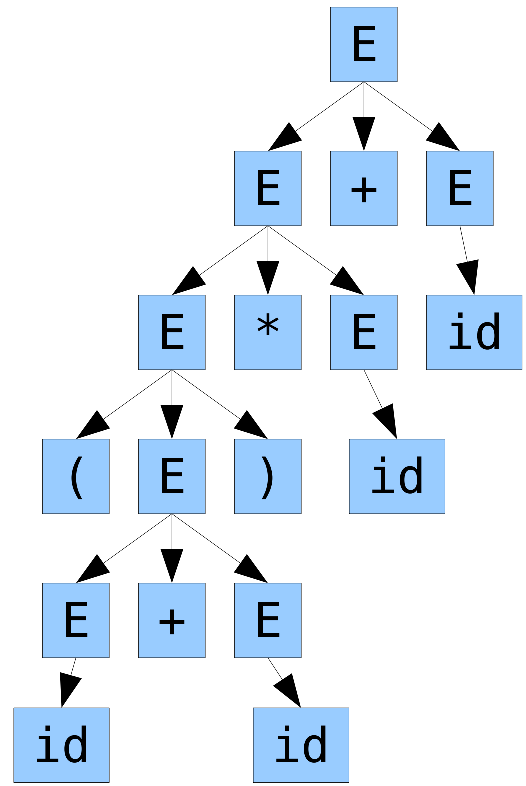
Derivations and Parse Trees

```
E
E + E
E + id
E * E + id
E * id + id
( E ) * id + id
( E + E ) * id + id
( id + E ) * id + id
( id + id ) * id + id
```



Left-Recursion

- Left-recursion makes parsing difficult
- Immediate left recursion:
  - $A \rightarrow A\alpha \mid \beta$
  - Rewrite as: $A \rightarrow \beta A'$ and $A' \rightarrow \alpha A' \mid \varepsilon$
- More complicated left recursion
  - $A \rightarrow^{+} A\alpha$

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Left Factoring

- Makes a grammar suitable for top-down parsing
- For each non-terminal *A* find the longest prefix α common to two or more alternatives
  - Replace $A \rightarrow \alpha \beta_1 \mid \alpha \beta_2 \mid \alpha \beta_3 \mid \ldots \mid \alpha \beta_n$ with
  - $A \rightarrow \alpha A'$ and $A' \rightarrow \beta_1 \mid \beta_2 \mid \beta_3 \mid \ldots \mid \beta_n$
- Repeat until not two alternatives have a common prefix

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Exercise

```
rexpr    → rexpr + rterm | rterm
rterm    → rterm rfactor | rfactor
rfactor  → rfactor * | rprimary
rprimary → a | b
```

- **Exercise:**
  - Remove left recursion
  - Left-factor

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First and Follow

- FIRST(X) : The set of terminals that begin strings that can be derived from X
- FOLLOW(X): The set of terminals that can appear immediately to the right of X in some sentential form
- **Be able to:**
  - compute FIRST and FOLLOW for a small example

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FIRST and FOLLOW Example

$$
\begin{aligned}
E &\rightarrow T\ E' \\
E' &\rightarrow +\ T\ E'\ |\ \varepsilon \\
T &\rightarrow F\ T' \\
T' &\rightarrow *\ F\ T'\ |\ \varepsilon \\
F &\rightarrow (\ E\ )\ |\ \textbf{id}
\end{aligned}
$$

- FIRST(F) = FIRST(T) = FIRST(E) = {(, id }
- FIRST(E') = {+, ε}
- FIRST(T') = {*, ε}
- FOLLOW(E) = FOLLOW(E') = {), $}
- FOLLOW(T) = FOLLOW(T') = {+,),$}
- FOLLOW(F) = {+, *,), $}

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LL(1) Grammars

- Left to right parsers producing a leftmost derivation looking ahead by at most 1 symbol
- Grammar G is LL(1) iff for every two productions of the form $A \rightarrow \alpha \mid \beta$
  - FIRST(α) and FIRST(β) are disjoint
  - If ε is in FIRST(β) then FIRST(α) and FOLLOW(A) are disjoint (and vice versa)

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LL(1) Parser

- LL(1) Parsers are driven by a table
  - Non-terminal x Next token => Expansion
- **Be able to:**
  - fill in a table given the FIRST and FOLLOW sets
  - use a table to parse an input string

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Bottom-up Parsing

- Shift-reduce parsing
  - Won't be covered on the exam

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Type-Checking

- Type checking is done by a bottom-up traversal of the parse tree
  - For each type of node, define what type it evaluates to given the types of its children
  - Some extra types may be introduced
    - error type
    - unknown type
  - These can be used for error recovery
- Environments
  - Used for keeping track of types of variables
  - Static lexical scoping
- **Exercise:**
  - pick a parse tree and assign types to its nodes

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Parse DAGs

- Parse DAGS
  - Like parse trees
  - Common subexpressions get merged
- **Exercise:**
  - Construct the parse DAG for
    - (x+y)-((x+y)*(x-y))
    - ((x1-x2)*(x1-x2))+((y1-y2)*(y1-y2))

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Intermediate Code Generation

- Two kinds of intermediate code
  - Stack machine
  - 3 address instructions
- For 3AI
  - Assign temporary variables to internal nodes of parse dags
  - output the instructions in reverse topological order
- For stack machines
  - just like in assignment 3
- Recipes for control structures

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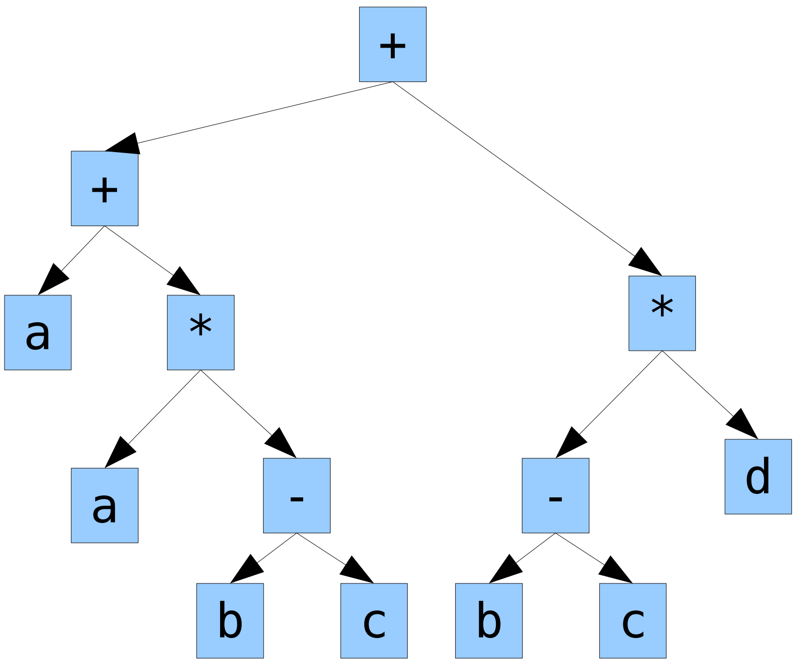
Example

- **Exercise:** Generate 3AI and stack-machine code for this parse tree



Scope and Code Generation

- The interaction between static lexical scope and the machine stack
  - Frame pointers
  - Parent frame pointers
  - The frame pointer array
- Object scope
  - Inheritance
  - Virtual methods
    - dispatch tables
- **Be able to:**
  - Illustrate state of stack fp, and fpp for a function call
  - Illustrate memory-layout of an OOP-language object

Basic Blocks

- Blocks of code that always execute from beginning to end
- **Be able to:**
  – Given a program, compute the basic blocks
- Next-use information:
  – Lazy algorithm for code generation and register usage based on next-use information
- **Be able to:**
  – Compute next-use information for all the variables in a basic block
  – Illustrate a register allocation based on next-use information
- The dangers of pointers and arrays

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Basic Blocks as DAGS

- Applications
  - Dead-code elimination, algebraic identities, associativity, etc
- **Be able to:**
  - Given a basic block, compute its DAG representation
  - Reassemble a basic block from its DAG
    - be careful with pointers and arrays

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Peephole Optimization

- Different kinds of peephole optimizations
  - redundant load/stores
  - unreachable code
  - flow of control optimizations (shortcuts)
  - algebraic simplifications and reduction in strength

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The Control Flow Graph

- Indicates which basic blocks may succeed other basic blocks during execution
- **Be able to:**
  - Compute a control flow graph
  - Choose register variables based on the control-flow graph
  - Eliminate unreachable code
  - Find no-longer-used variables
  - Compute the transitive closure

Register Allocation by Graph Coloring

- The interference graph
  - nodes are variables
  - two nodes are adjacent if the variables are active simultaneously
  - Color the graph with the minimum number of colors
- Inductive graph coloring algorithm
  - Delete vertex of lowest degree
  - Recurse
  - Reinsert vertex and color with lowest available color
- **Be able to:**
  - Illustrate inductive coloring algorithm

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Ershov Numbers

- Computed by bottom-up traversal of parse tree
- Represent the minimum number of registers required to avoid loads and stores
- Dynamic programming extension
  - reorderings of children
  - different instructions
- **Be able to:**
  - Compute Ershov numbers
  - Compute dynamic programming costs

Data-Flow Analysis

- Define in and out
  - for each line of code
  - for each basic block
- Define transfer functions
  - out[L] = f(L, in[L])
  - in[B] = f(out[B1],…,out[Bk])
    - where B1,…,Bk are predecessors of B
  - Sometimes works backwards
- Example applications
  - reaching definitions, undefined variables, live variable analysis
- **Be able to:**
  - Apply iterative algorithm for solving equations

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The GNU Compiler Collection

- History and background
  - Started in 1985
  - Open source
  - Compilation steps:
    - Input language
    - Parse tree
    - GENERIC
    - GIMPLE
    - RTL
    - Machine language

- **Be able to:**
  - Recognize a picture of Richard Stallman
  - Know difference between GENERIC and GIMPLE

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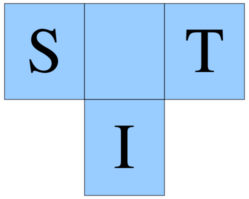
Want to Build a Compiler

- Cross-compiling
- Bootstrapping
- Self compiling
- T-diagrams
- **Be able to:**
  - Understand T-diagrams
  - Solve a cross-compilation problem



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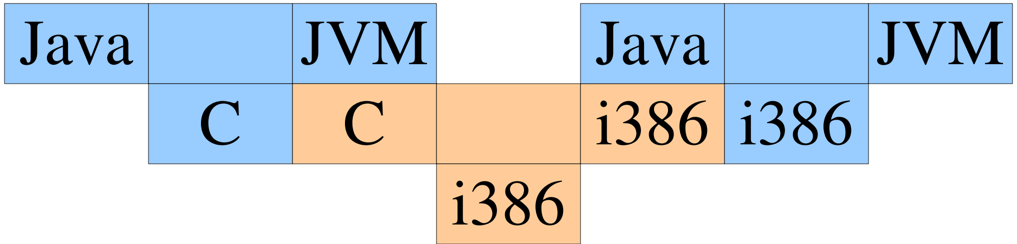

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LL(1) Parser

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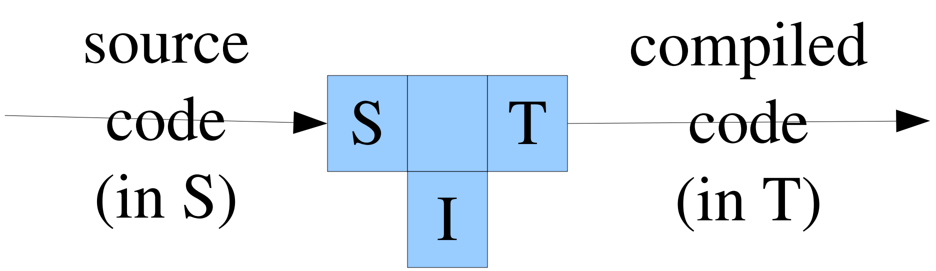
Want to Write a Compiler?

- A compiler has 3 main parameter
  - Source language (S)
    - What kind of input does the compiler take?
    - C, C++, Java, Python, ...
  - Implementation language (I)
    - What language is the compiler written in?
    - C, Java, i386, x84_64
  - Target language (T)
    - What is the compiler's target language
    - i386, x86_64, PPC, MIPS, ...



Source Language Issues

- Complexity
  - Is a completely handwritten compiler feasible?
- Stability
  - Is the language definition still changing?
- Novelty
  - Do there already exist compilers for this language?
- Complicated, or still-changing languages promote the use of compiler generation tools

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Target Language Issues

- Novelty
  - Is this a new architecture?
  - Are there similar architectures/instruction sets?
- Available tools
  - Is there an assembler for this language?
  - Are there other compilers for this language?

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Performance criteria

- Speed
  - Does it have to be a fast compiler?
  - Does it have to be a small compiler?
  - Does it have to generate fast code?
- Portability
  - Should the compiler run on many different architectures (*rehostability*)
  - Should the compiler generate code for many different architectures (*retargetability*)

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Possible Workarounds

- Rewrite an existing front end
  - when the source is new
  - reuse back (code generation) end of the compiler
- Rewrite an existing back end
  - when the target architecture is new
  - retarget an existing compiler to a new architecture
- What happens when both the source language and target language are new?
  - Write a compiler from scratch?
  - Do we have other options?

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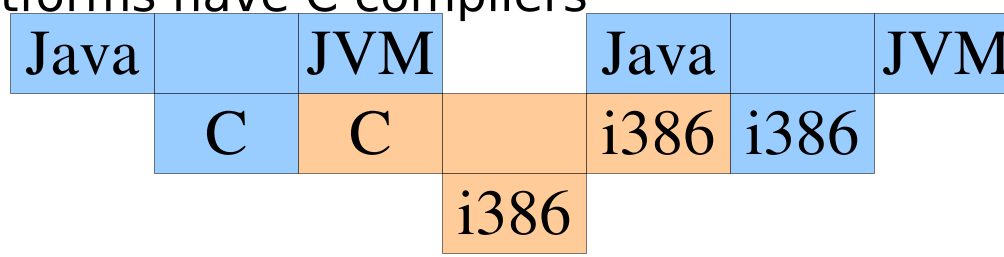
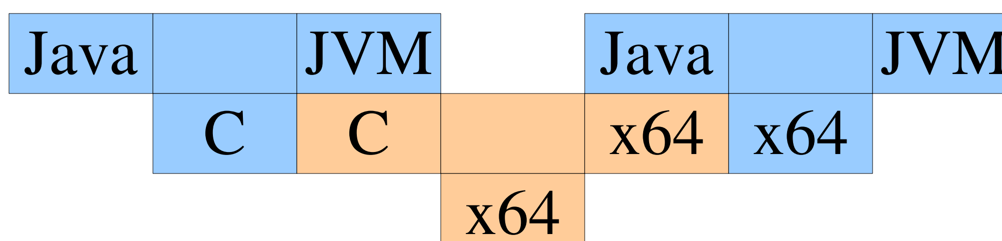
Composing Compilers

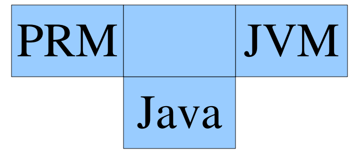
- Compilers can be composed and used to compile each other
- Example:
  - We have written a Java to JVM compiler in C and we want to make it to run on two different platforms i386 and x86_64
  - both platforms have C compilers



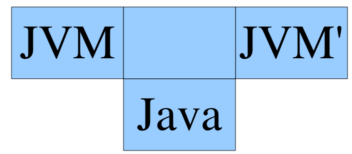


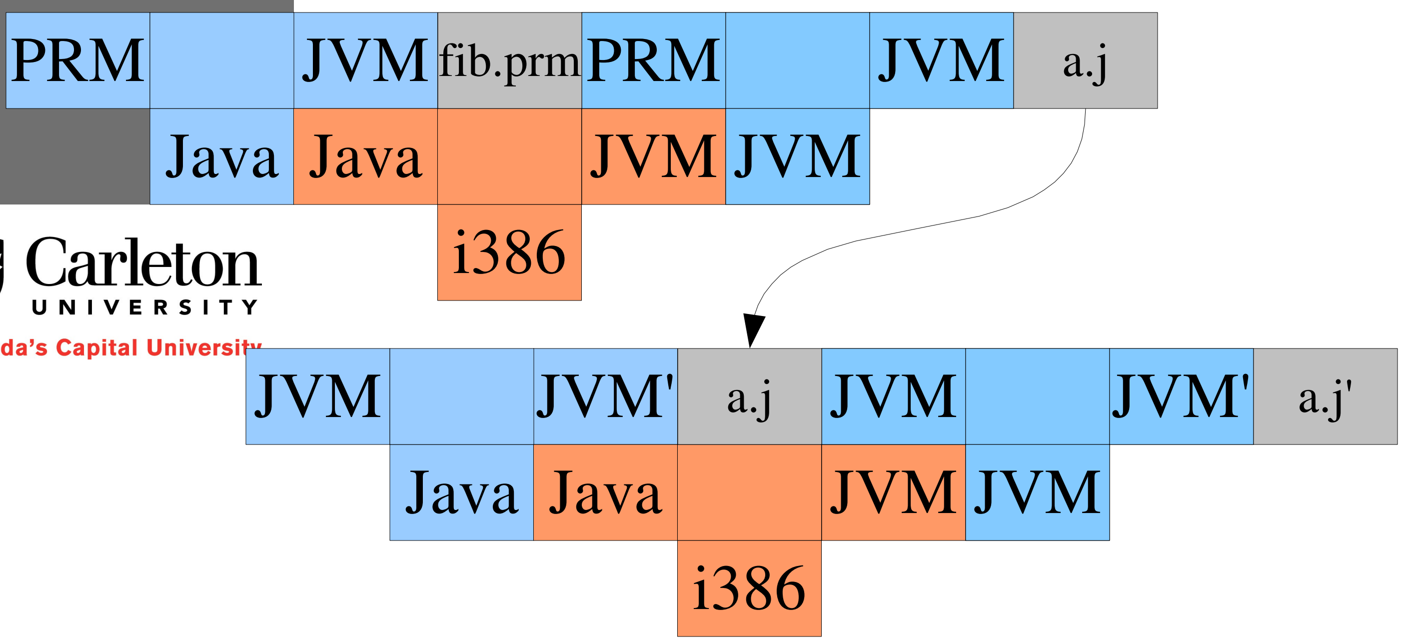
Example

- Assignment 3:



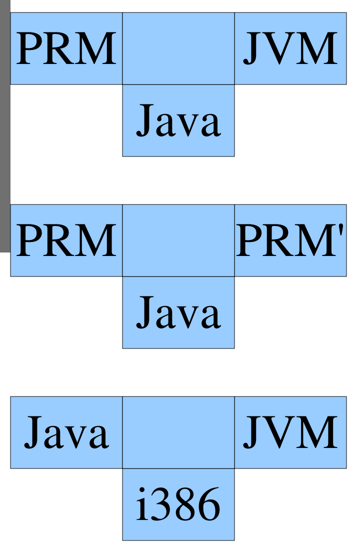
- Assignment 4:





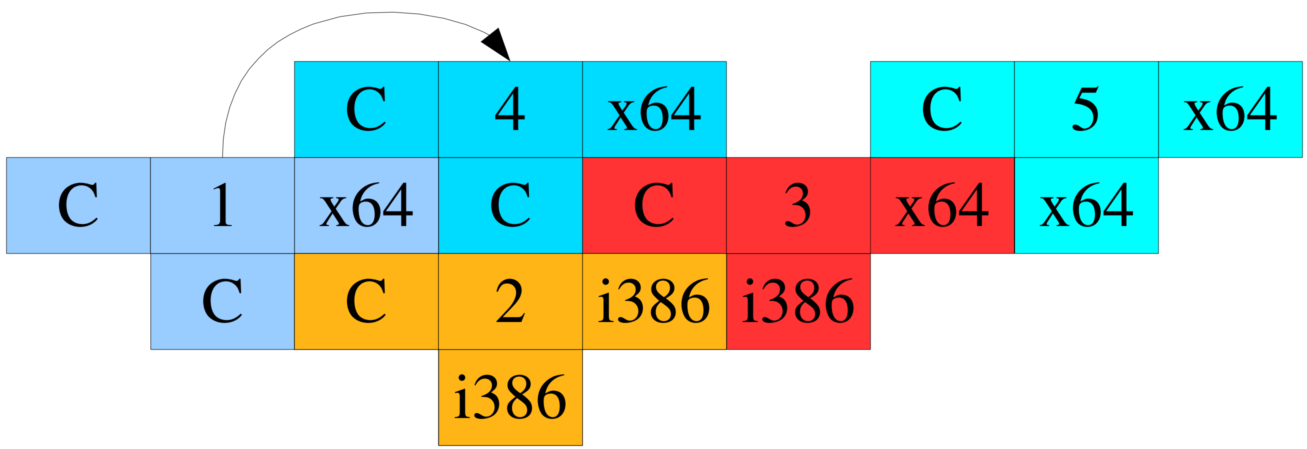
Example

- Show how to
  - To take your PRM compiler and make it faster
  - To take your Jasmin optimizer and make it faster



Bootstrapping by cross-compiling

- Sometimes the source and implementation language are the same
  - E.g. A C compiler written in C
- In this case, cross compiling can be useful



Bootstrapping Cont'd

- Bootstrapping by reduced functionality
  - Implement, in machine language, a simplified compiler
    - A subset of the target language
    - No optimizations
  - Write a compiler for the full language in the reduced language

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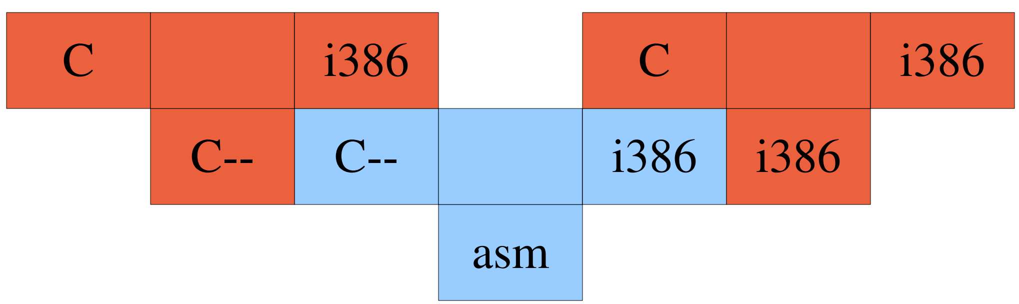
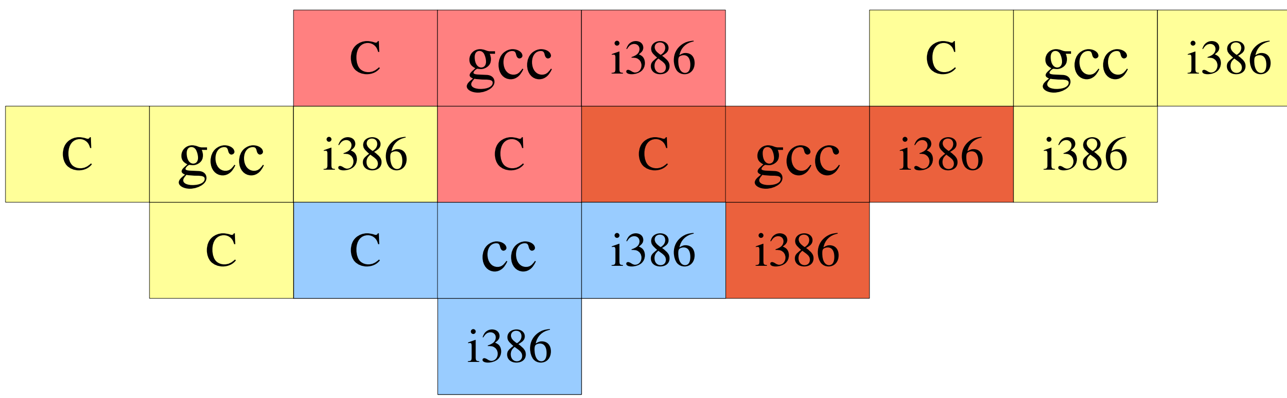


Bootstrapping for Self-Improvement

- If we are writing a good optimizing compiler with I=S then
  - We can compile the compiler with itself
  - We get a fast compiler
- gcc does this (several times)



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Summary

- When writing a compiler there are several techniques we can use to leverage existing technology
  - Reusing front-ends or back ends
  - Cross-compiling
  - Starting from reduced instruction sets
  - Self-compiling

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