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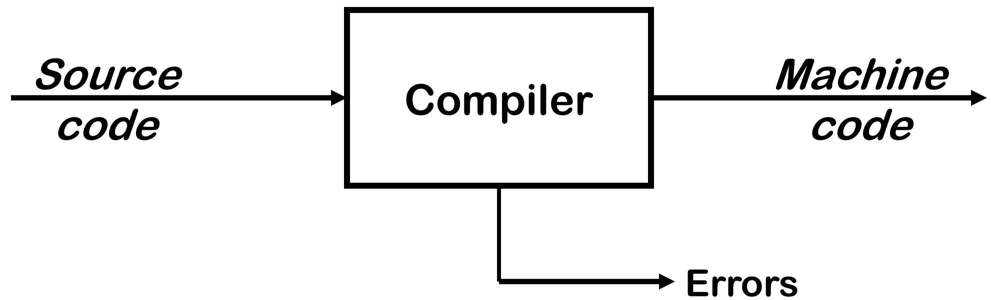
Compilers
Design and Implementation

Overview of a Compiler

High-level View of a Compiler

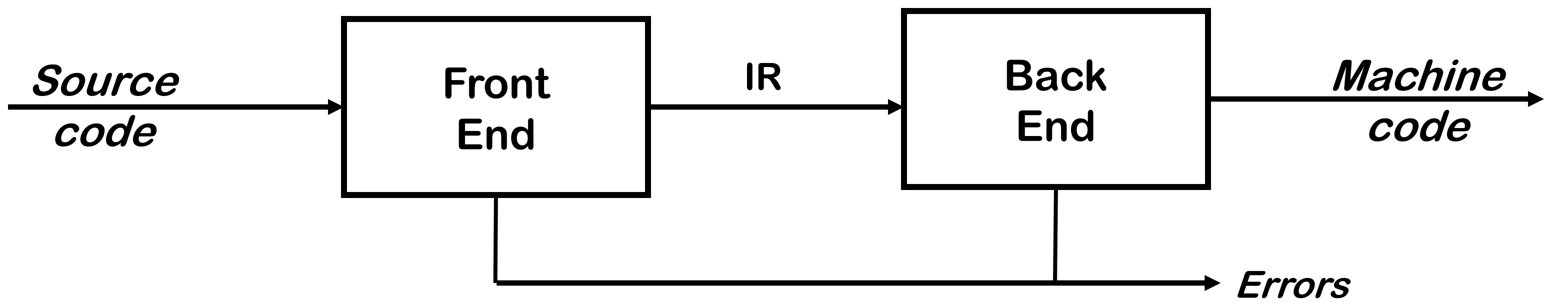


Implications:

- Must recognize legal (and illegal) programs
- Must generate correct code
- Must manage storage of all variables (and code)
- Must agree with OS & linker on format for object code

Big step up from assembly language—use higher level notations

Traditional Two-pass Compiler

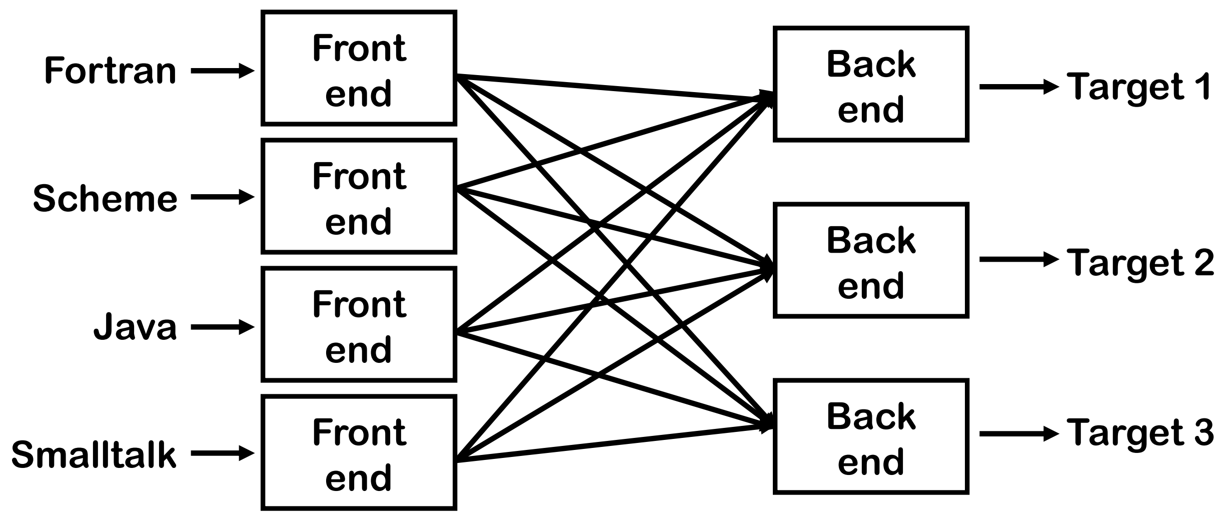


Implications

- Use an intermediate representation (IR)
- Front end maps legal source code into IR
- Back end maps IR into target machine code
- Admits multiple front ends & multiple passes *(better code)*

Typically, front end is O(n) or O(n log n), while back end is NPC

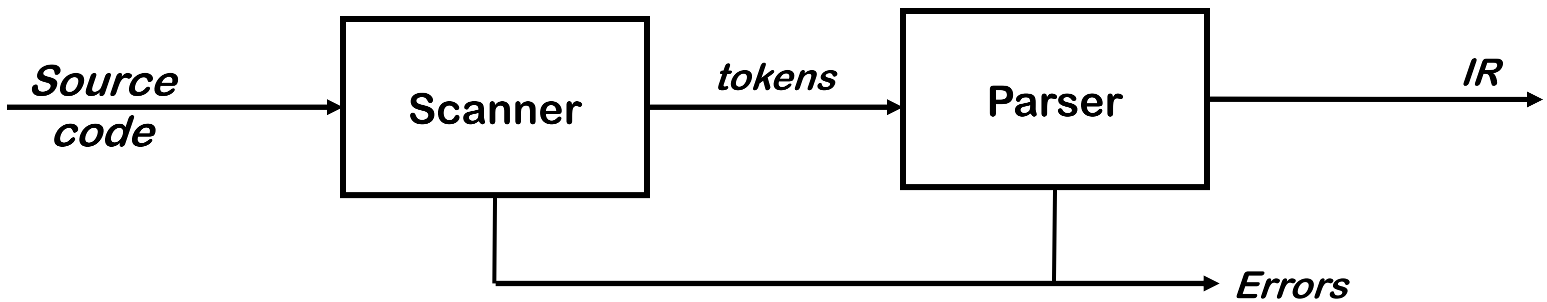
A Common Fallacy



Can we build *n x m* compilers with *n+m* components?

- Must encode all language specific knowledge in each front end
- Must encode all features in a single IR
- Must encode all target specific knowledge in each back end

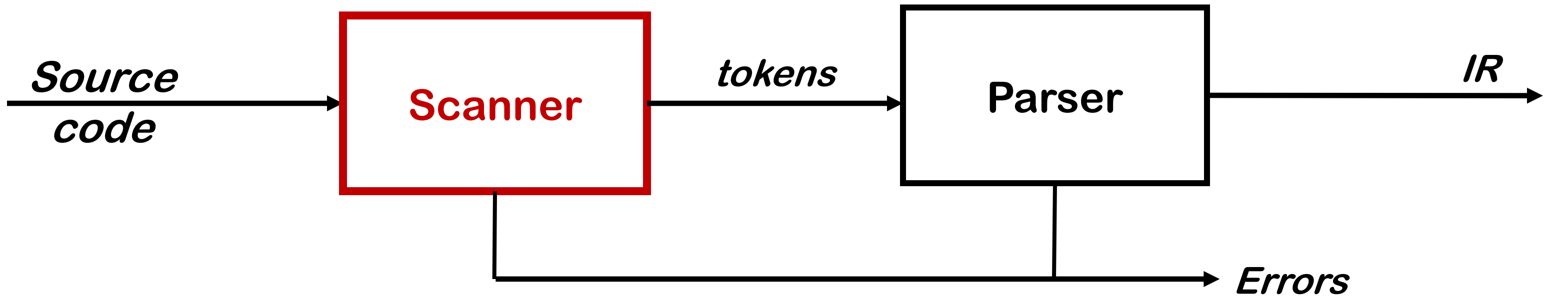
The Front End



Responsibilities

- Recognize legal (& illegal) programs
- Report errors in a useful way
- Produce IR & preliminary storage map
- Shape the code for the back end
- Much of front end construction can be automated

The Front End



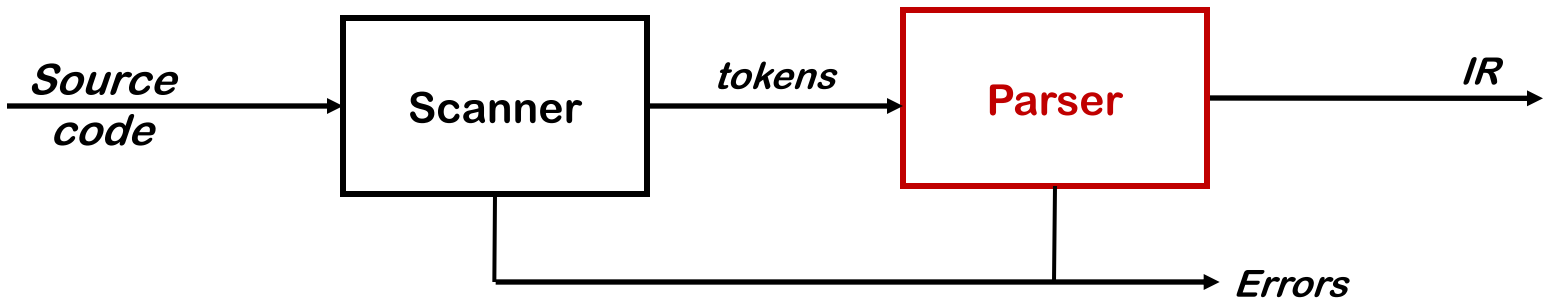
Scanner

- Maps character stream into words—the basic unit of syntax
- Produces pairs — a word & its part of speech

  x = x + y ; *becomes* <id,x> = <id,x> + <id,y> ;

  – *word ≅ lexeme, part of speech ≅ token type*
  – In casual speech, we call the pair a *token*
- Typical tokens include *number*, *identifier*, +, –, new, *while*, *if*
- Scanner eliminates white space (*including comments*)
- Speed is important

The Front End



Parser

- Recognizes context-free syntax & reports errors
- Guides context-sensitive ("semantic") analysis (*type checking*)
- Builds IR for source program

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The Front End

Context-free syntax is specified with a grammar

$$\begin{aligned} \mathit{SheepNoise} &\rightarrow \mathit{SheepNoise}\ \underline{\text{baa}} \\ &\mid\ \underline{\text{baa}} \end{aligned}$$

This grammar defines the set of noises that a sheep makes under normal circumstances

It is written in a variant of Backus–Naur Form (BNF)

Formally, a grammar $G = (S,N,T,P)$

- S is the *start symbol*
- N is a set of *non-terminal symbols*
- T is a set of *terminal symbols* or *words*
- P is a set of *productions* or *rewrite rules* $(P : N \rightarrow N \cup T)$

The Front End

Context-free syntax can be put to better use…

1.	*goal*	→	*expr*
2.	*expr*	→	*expr op term*
3.		→	*term*
4.	*term*	→	number
5.		→	id
6.	*op*	→	+
7.		→	-

S = *goal*

T = { number, id, +, - }

N = { *goal*, *expr*, *term*, *op* }

P = { 1, 2, 3, 4, 5, 6, 7}

- This grammar defines simple expressions with addition & subtraction over "number" and "id"
- This grammar, like many, falls in a class called "context-free grammars", abbreviated CFGs

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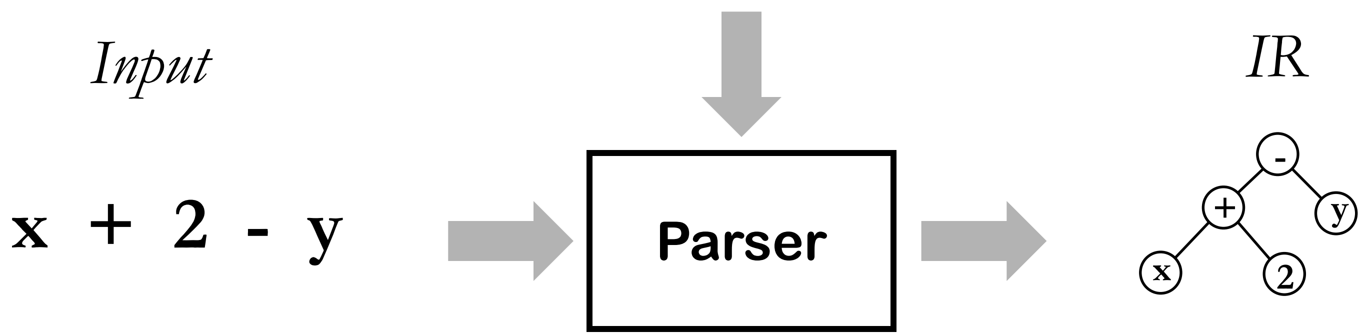
The Front End

CFG

1. *goal* → *expr*
2. *expr* → *expr op term*
3. → *term*
4. *term* → <u>number</u>
5. → <u>id</u>
6. *op* → +
7. → -



The Front End

Given a CFG, we can ***derive*** sentences by repeated substitution

Production	Result
	goal
1	*expr*
2	*expr op term*
5	*expr op* id
7	*expr* - id
2	*expr op term* - id
4	*expr op* number - id
6	*expr* + number - id
3	*term* + number - id
5	id + number - id

⇕

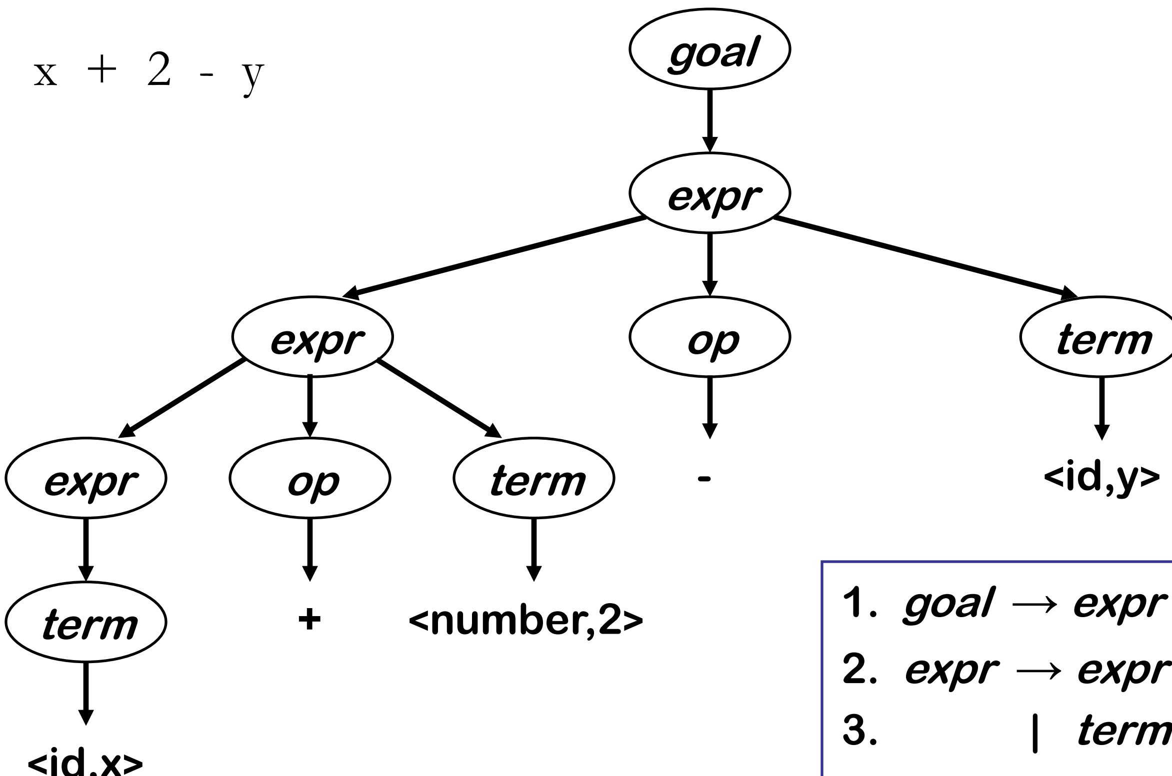
x + 2 - y

To recognize a valid sentence in some CFG, we reverse this process and build up a ***parse***

The Front End

A parse can be represented by a tree (***parse tree*** or ***syntax tree***)

x + 2 - y

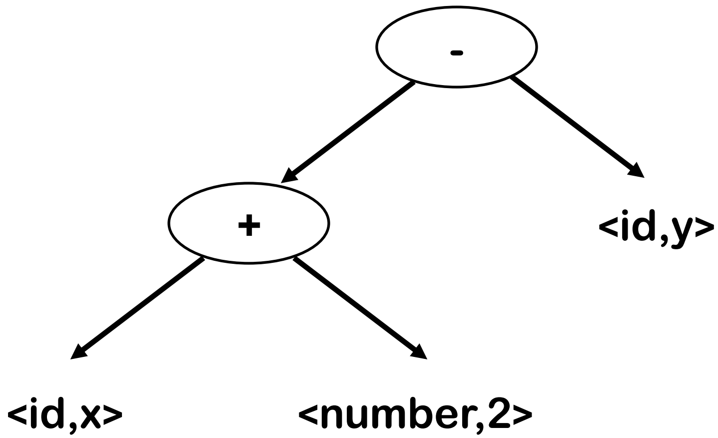


1. *goal* → *expr*
2. *expr* → *expr op term*
3. | *term*
4. *term* → <u>number</u>
5. | <u>id</u>
6. *op* → +
7. | -

This contains a lot of unneeded information.

The Front End

Compilers often use an ***abstract syntax tree***

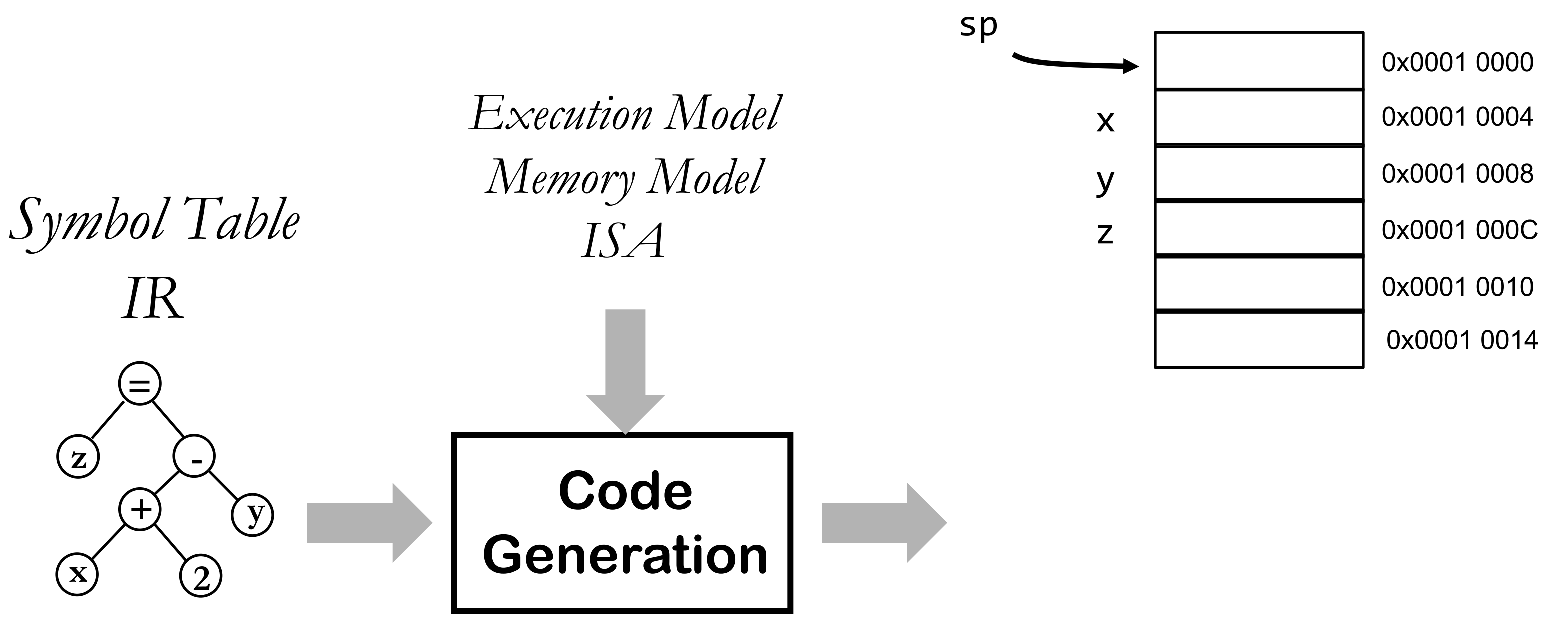


The AST summarizes grammatical structure, without including detail about the derivation

This is much more concise

ASTs are one kind of *intermediate representation (IR)*

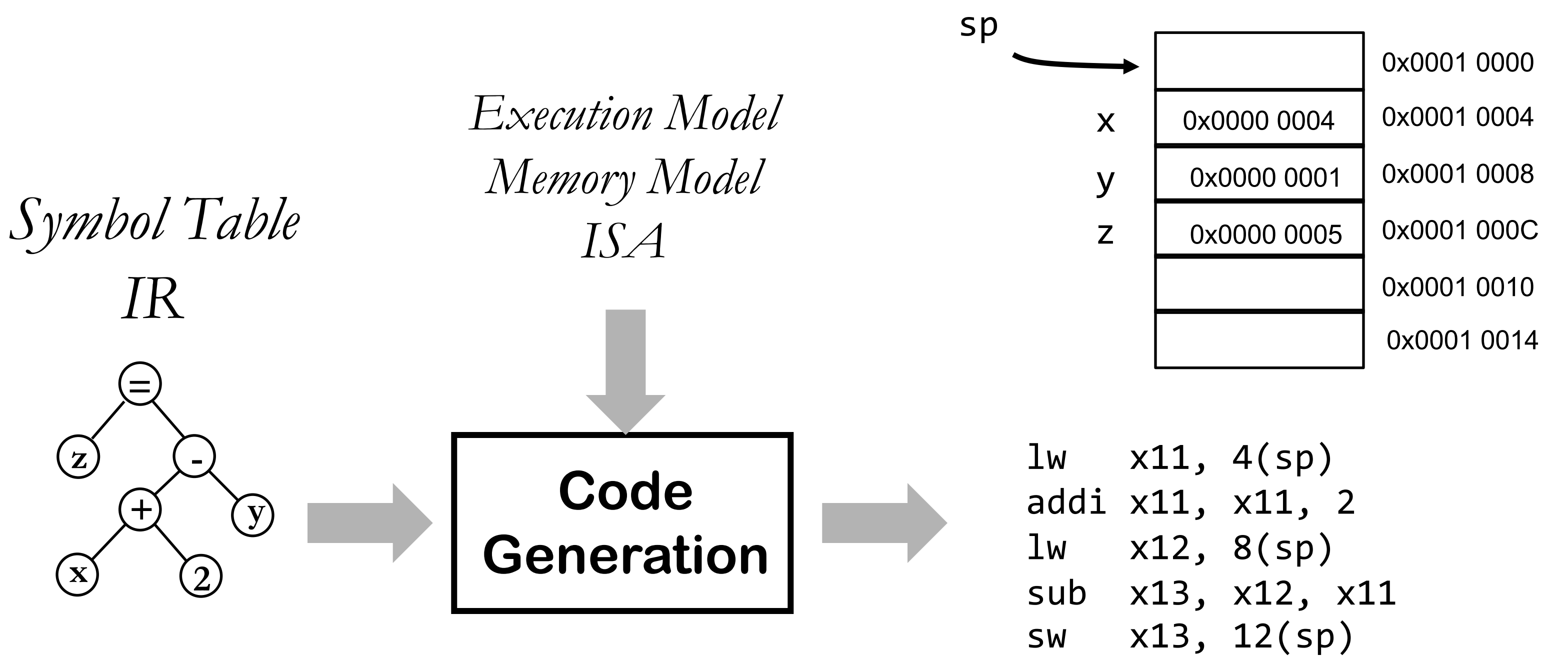
The Back End



Basic Code Generation Issues:

- What types of values name represent?
- How to map control-flow to low-level code?
- Where are names visible in the program(scope)?
- Where are the names mapped to at run-time?
- Role of recursion and function call

The Back End



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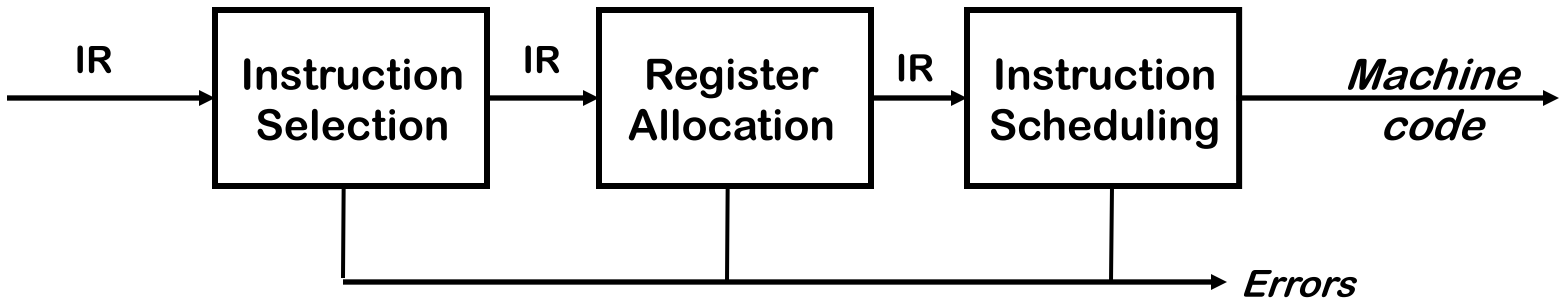
The Back End

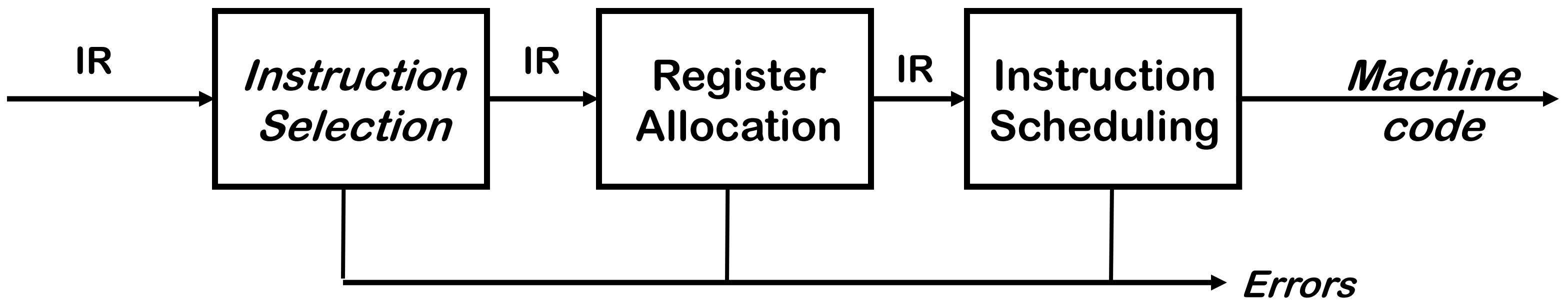


Responsibilities

- Translate IR into target machine code
- Choose instructions to implement each IR operation
- Decide which value to keep in registers
- Ensure conformance with system interfaces

Automation has been *less* successful in the back end

The Back End



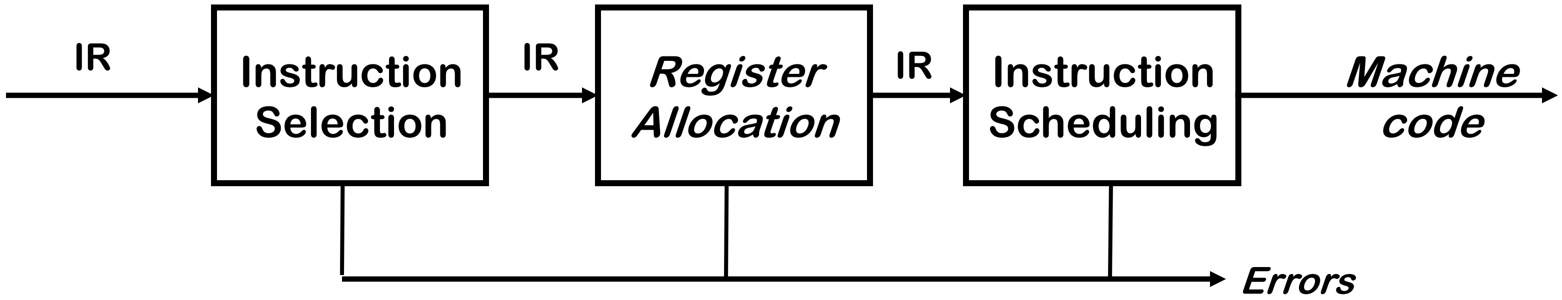
Instruction Selection

- Produce fast, compact code
- Take advantage of target features such as addressing modes
- Usually viewed as a pattern matching problem
  - *ad hoc* methods, pattern matching, dynamic programming

This was the problem of the future in 1978

- Spurred by transition from PDP-11 to VAX-11
- Orthogonality of RISC simplified this problem

The Back End

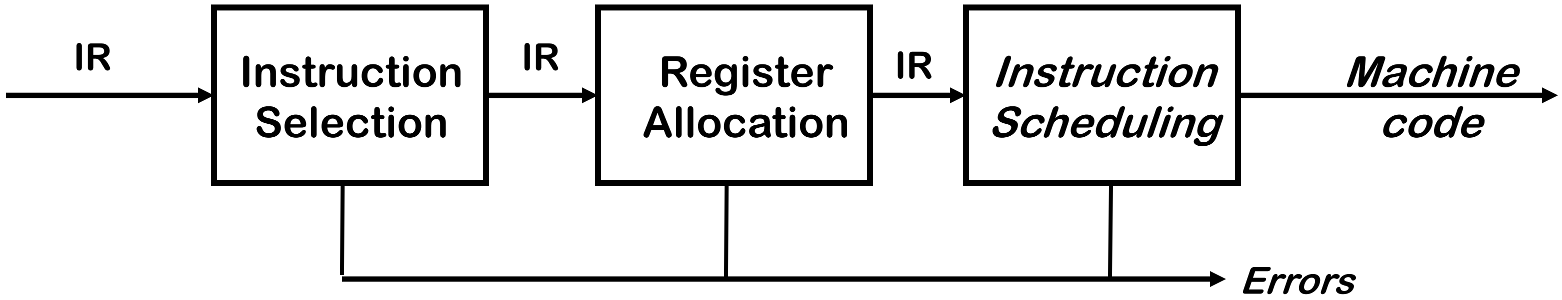


Register Allocation

- Have each value in a register when it is used
- Manage a limited set of resources
- Can change instruction choices & insert LOADs & STOREs
- Optimal allocation is NP-Complete (1 or *k* registers)

Compilers approximate solutions to NP-Complete problems

The Back End



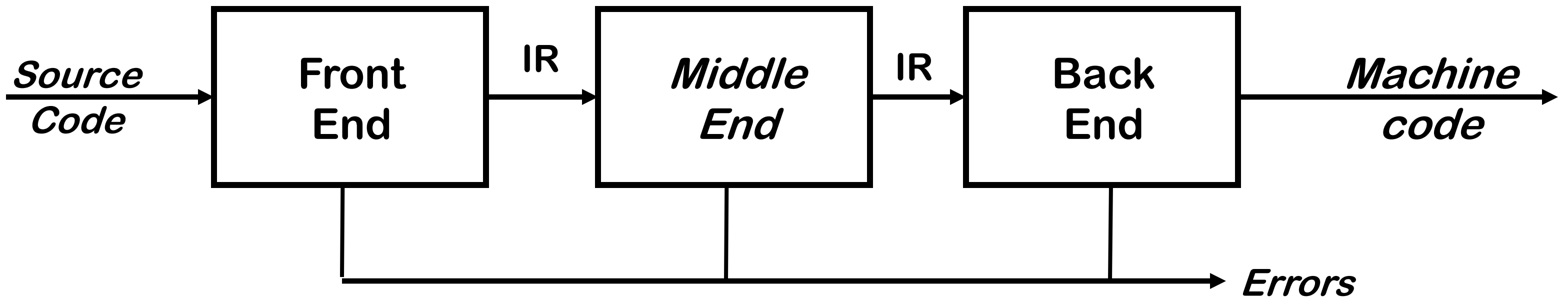
Instruction Scheduling

- Avoid hardware stalls and interlocks
- Use all functional units productively
- Can increase lifetime of variables (changing the allocation)

Optimal scheduling is NP-Complete in nearly all cases

Heuristic techniques are well developed

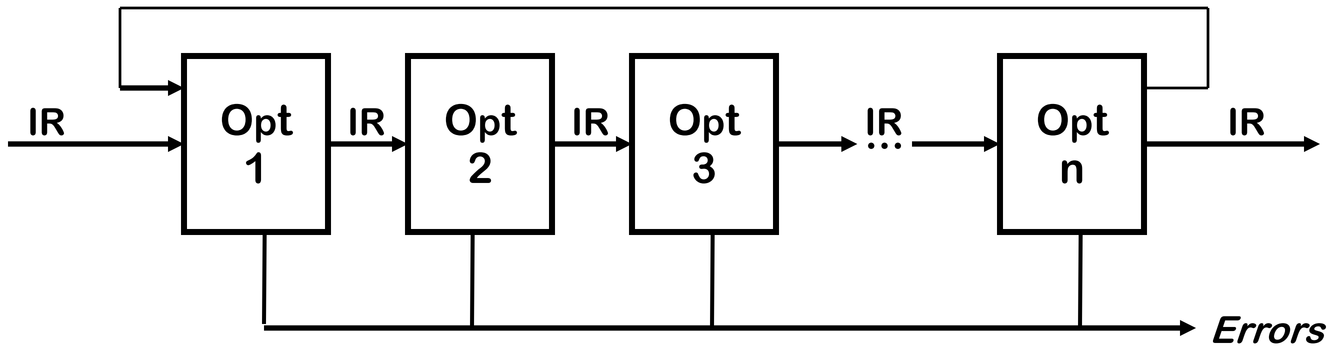
Traditional Three-pass Compiler



Code Improvement (or *Optimization*)

- Analyzes IR and Rewrites (or *transforms*) IR
- Primary goal is to reduce running time of the compiled code
  - May also improve space, power consumption, …
- Must Preserve "meaning" of the Code
  - Measured by values of named variables

The Optimizer (or Middle End)

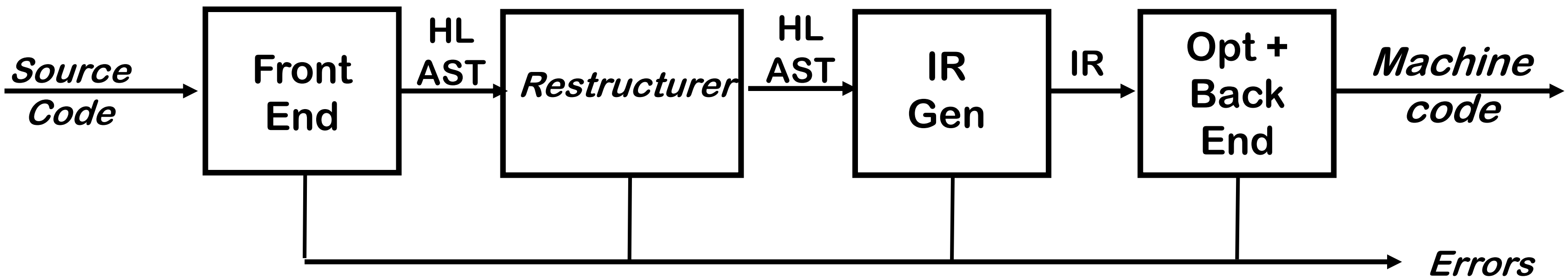


Modern optimizers are structured as a series of passes

Typical Transformations

- Discover & propagate some constant value
- Move a computation to a less frequently executed place
- Specialize some computation based on context
- Discover a redundant computation & remove it
- Remove useless or unreachable code
- Encode an idiom in some particularly efficient form

Modern Restructuring Compiler



Typical *Restructuring* Transformations:

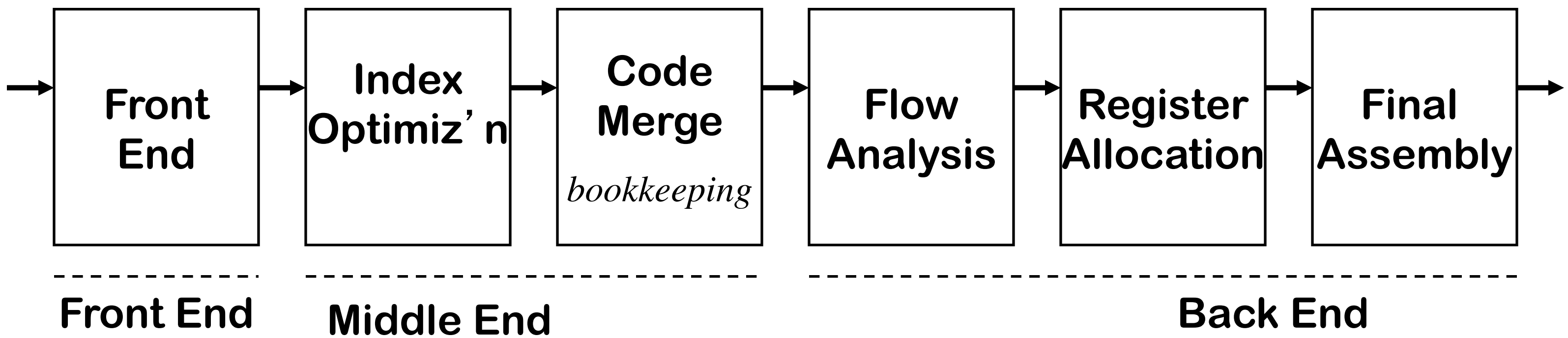
- Blocking for Memory Hierarchy and Register Reuse
- Vectorization
- Parallelization
- All based on dependence
- Also full and partial inlining

Role of the Run-Time System

- Memory Management Services
  - Allocate
    - In the heap or in an activation record (*stack frame*)
  - Deallocate
  - Collect garbage
- Run-time Type Checking
- Error Processing
- Interface to the Operating System
  - Input and Output
- Support of Parallelism
  - Parallel Thread initiation
  - Communication and Synchronization

Classic Compilers

1957: The FORTRAN Automatic Coding System



- Six passes in a fixed order
- Generated good code

  Assumed unlimited index registers

  Code motion out of loops, with ifs and gotos

  Did flow analysis & register allocation

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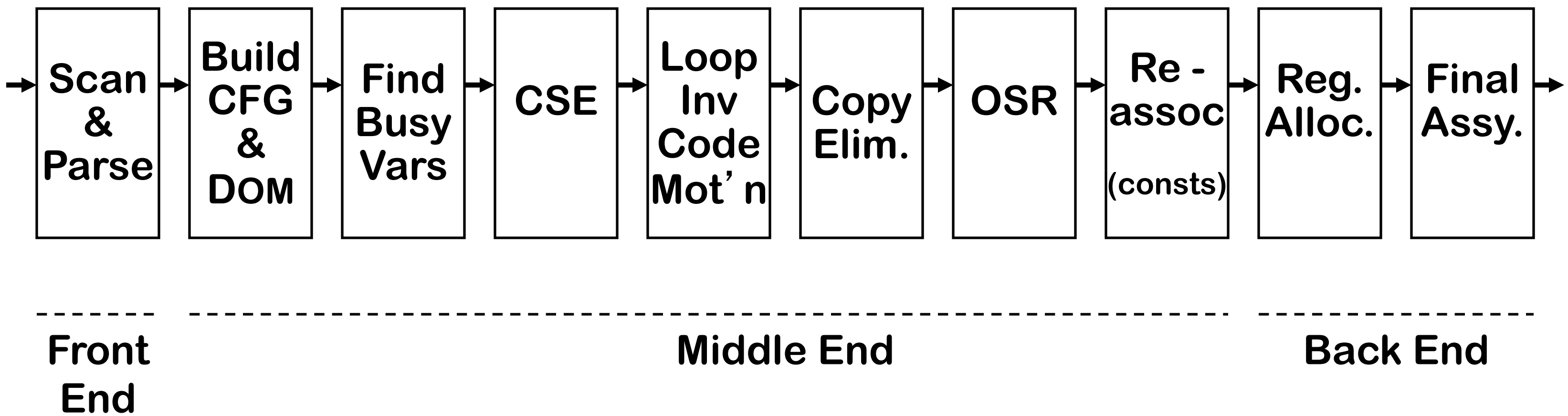
Classic Compilers

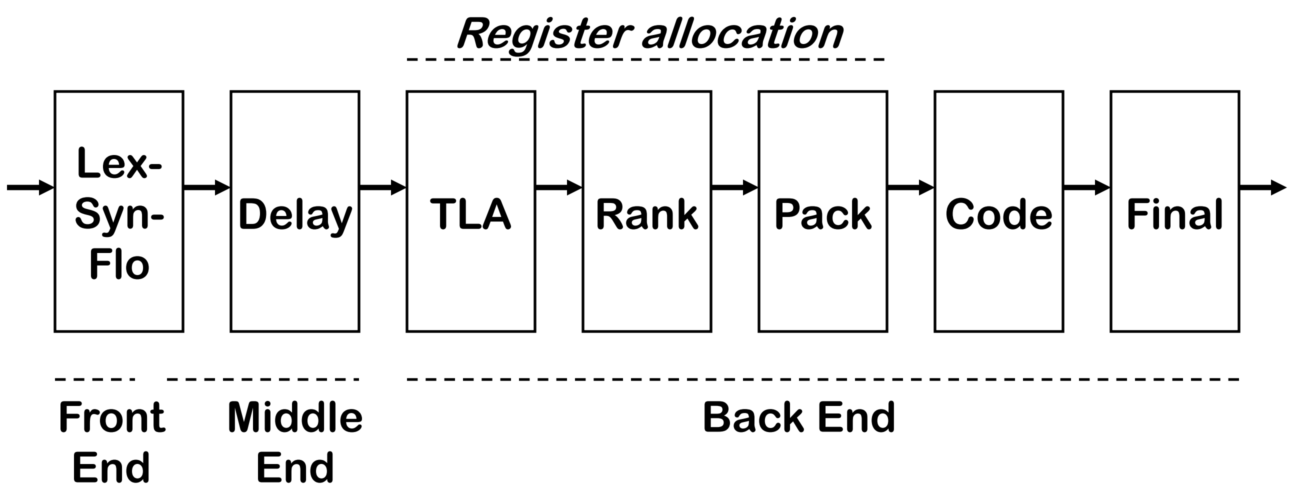
1969: IBM's FORTRAN H Compiler



- Used low-level IR (quads), identified loops with dominators
- Focused on optimizing loops ("inside out" order)
  - Passes are familiar today
- Simple front end, simple back end for IBM 370

Classic Compilers

1975: BLISS-11 compiler (Wulf *et al.*, CMU)

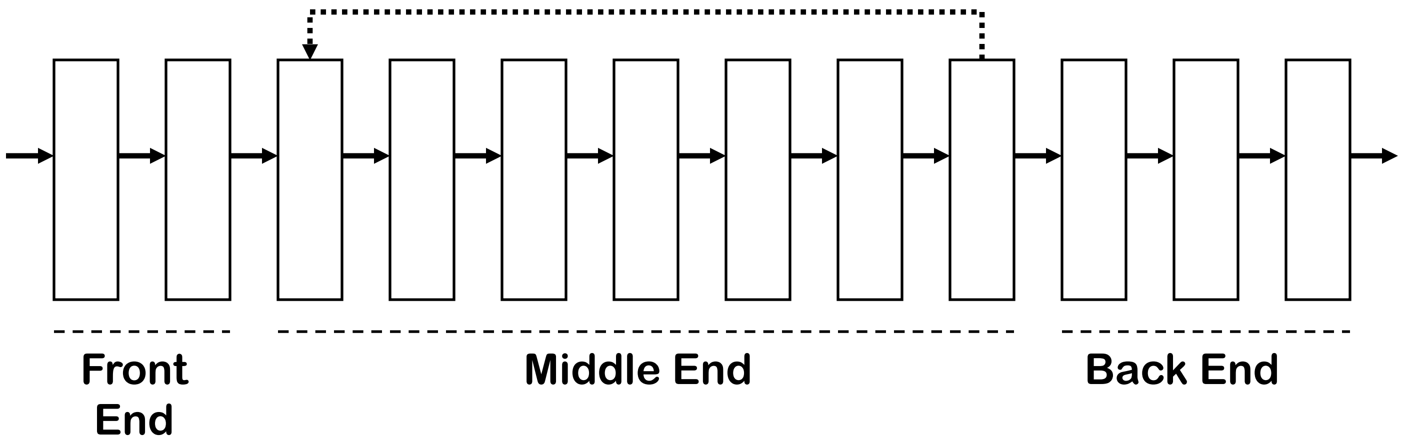


- The great compiler for the PDP-11
- Seven passes in a fixed order
- Focused on code shape & instruction selection
  - LexSynFlo did preliminary flow analysis
  - Final included a grab-bag of peephole optimizations

Basis for early VAX & Tartan Labs compilers

Classic Compilers

1980: IBM's PL.8 Compiler

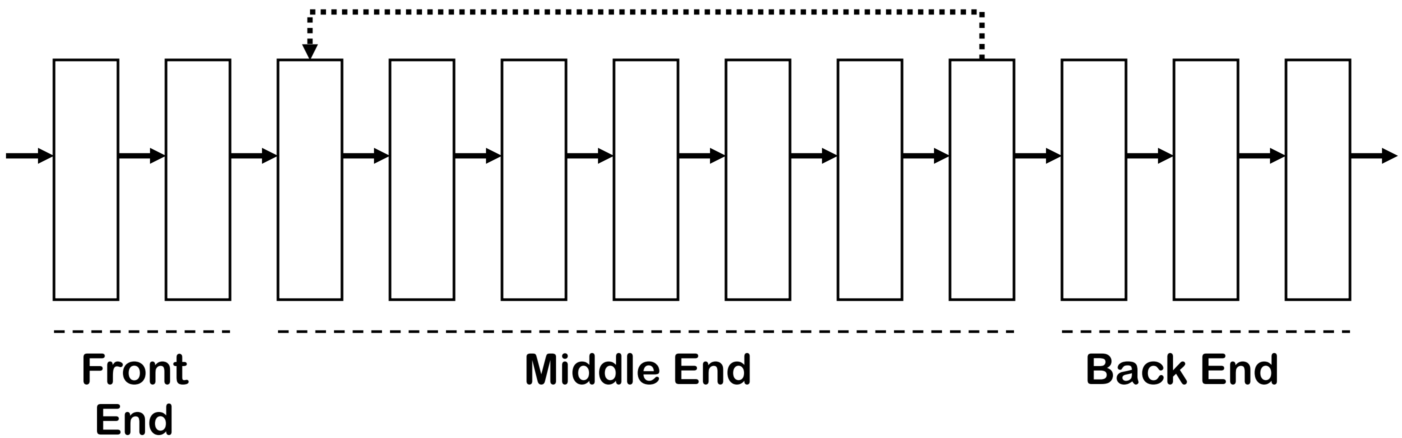


- Many passes, 1 front end, several back ends
- Collection of 10 or more passes
  - Repeat some passes and analyses
  - Represent complex operations at 2 levels
  - Below machine-level IR

Dead code elimination
Global CSE
Code motion
Constant folding
Strength reduction
Value numbering
Dead store elimination
Code straightening
Trap elimination
Algebraic reassociation

Classic Compilers

1980: IBM's PL.8 Compiler



- Many passes, 1 front end, several back ends
- Collection of 10 or more passes

  Repeat some passes and analyses

  Represent complex operations at 2 levels

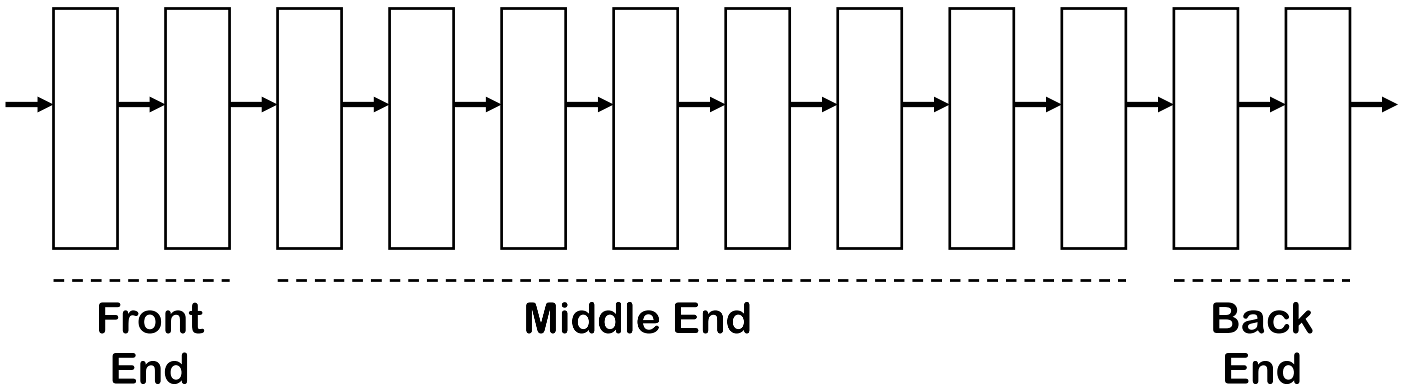
  Below machine-level IR

Multi-level IR has become common wisdom

*

Classic Compilers

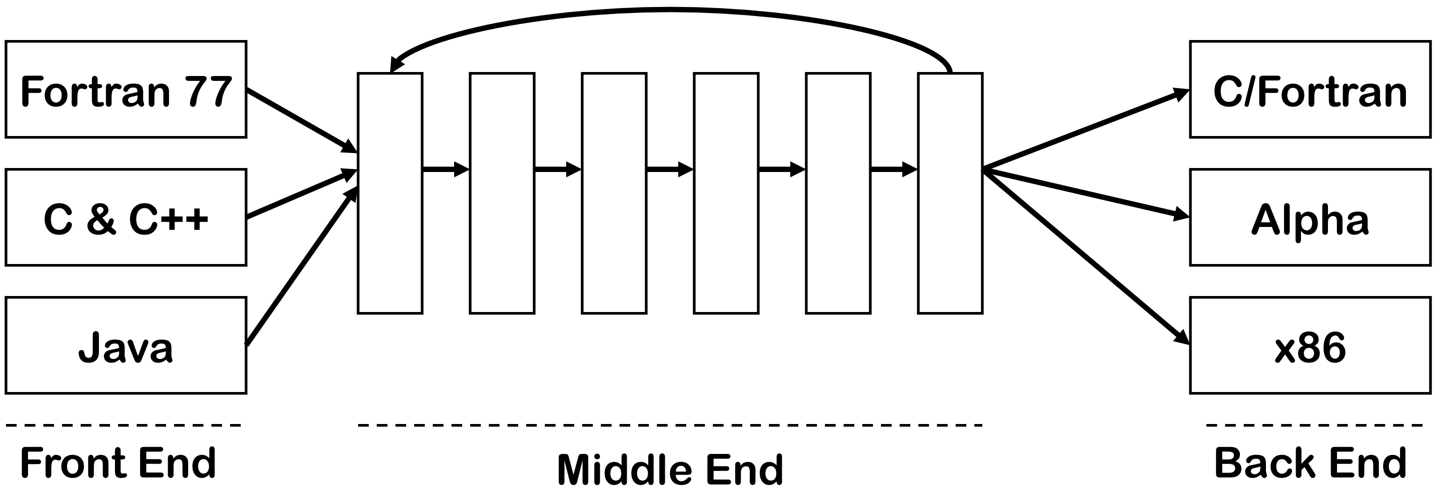
1986: HP’ s PA-RISC Compiler



- Several front ends, an optimizer, and a back end
- Four fixed-order choices for optimization (9 passes)
- Coloring allocator, instruction scheduler, peephole optimizer

Classic Compilers

1999: The SUIF Compiler System



Another classically-built compiler

- 3 front ends, 3 back ends
- 18 passes, configurable order
- Two-level IR (High SUIF, Low SUIF)
- Intended as research infrastructure

Classic Compilers

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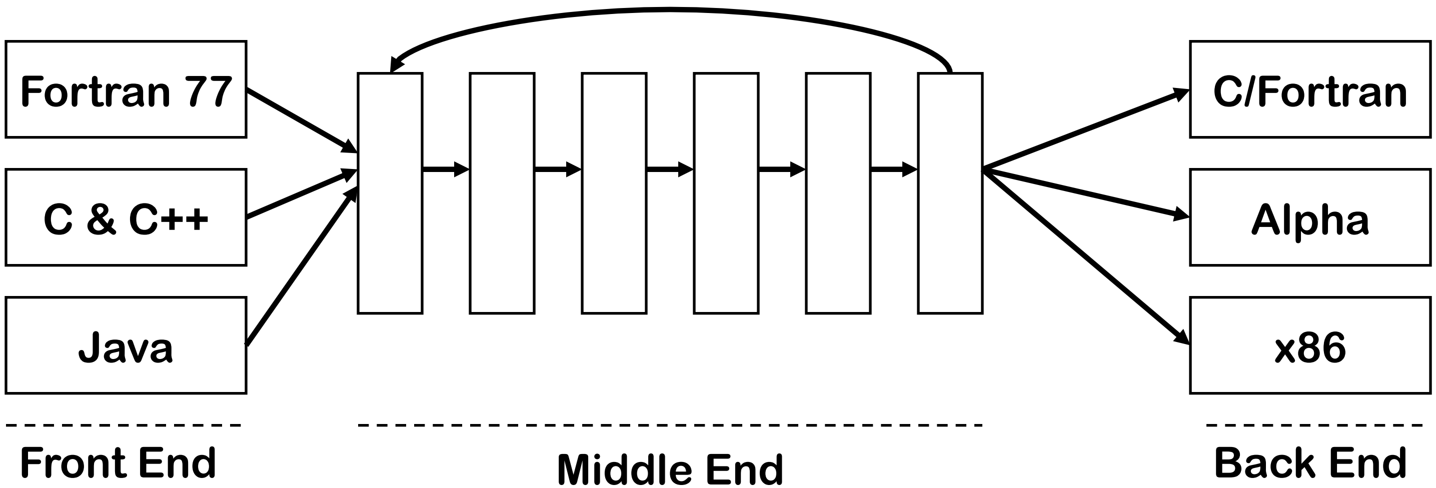


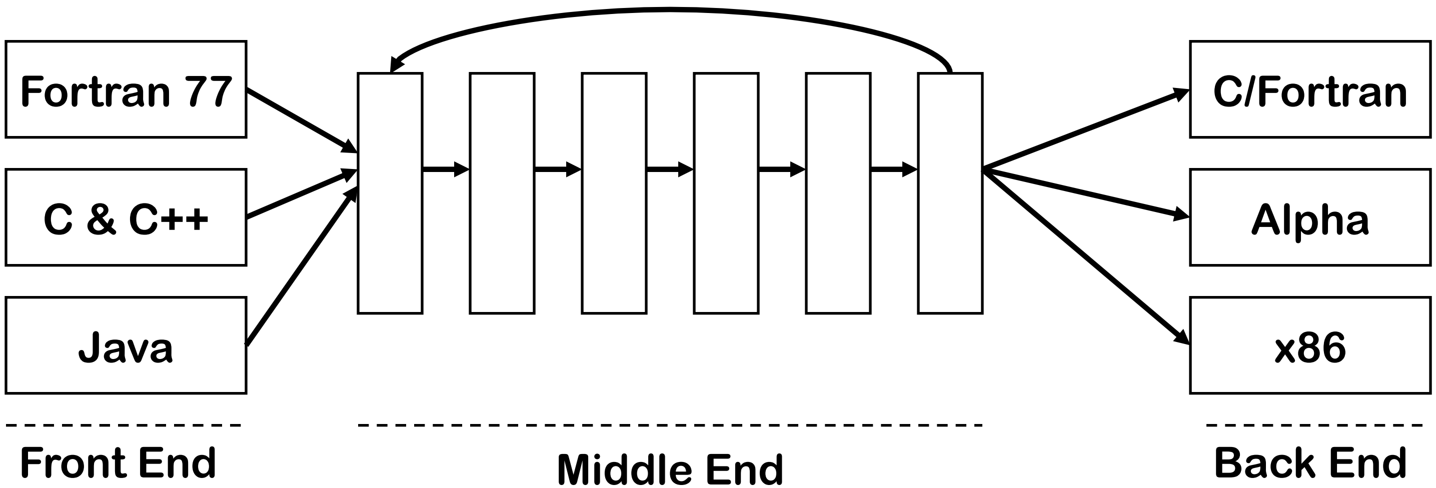
Another classically-built compiler

- 3 front ends, 3 back ends
- 18 passes, configurable order
- Two-level IR (High SUIF, Low SUIF)
- Intended as research infrastructure

SSA construction
Dead code elimination
Partial redundancy elimination
Constant propagation
Global value numbering
Strength reduction
Reassociation
Instruction scheduling
Register allocation

Classic Compilers

1999: The SUIF Compiler System



Another classically-built compiler

- 3 front ends, 3 back ends
- 18 passes, configurable order
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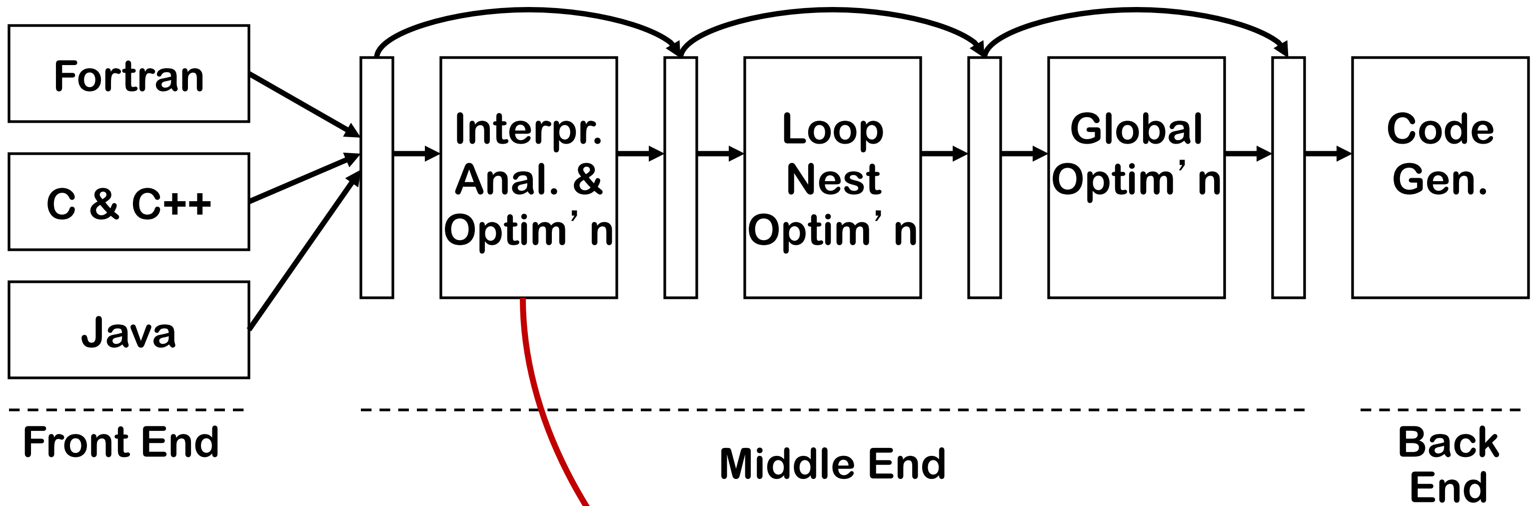
- Intended as research infrastructure

Data dependence analysis
Scalar & array privatization
Reduction recognition
Pointer analysis
Affine loop transformations
Blocking
Capturing object definitions
Virtual function call elimination
Garbage collection

Classic Compilers

2000: The SGI Pro64 Compiler (now Open64 from Intel)



Open source optimizing compiler for IA 64

- 3 front ends, 1 back end
- Five-levels of IR
- Gradual lowering of abstraction level

Interprocedural
Classic Analysis
Inlining (user & library code)
Cloning (constants & locality)
Dead function elimination
Dead variable elimination

Classic Compilers

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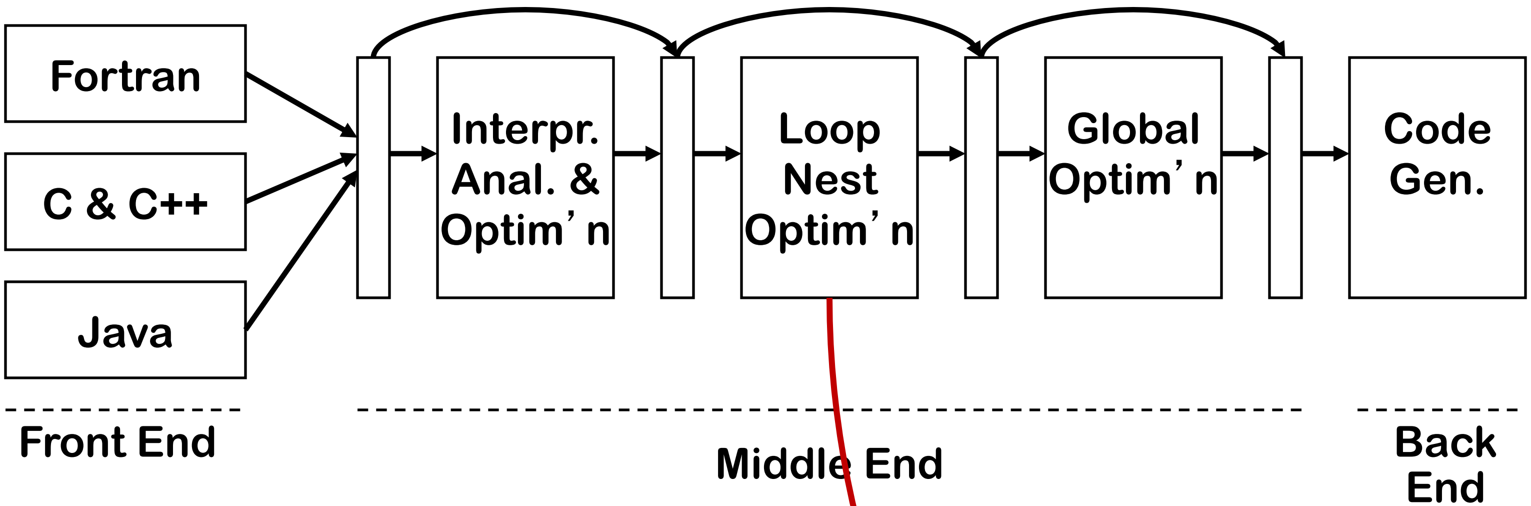

Open source optimizing compiler for IA 64

- 3 front ends, 1 back end
- Five-levels of IR
- Gradual lowering of abstraction level

Loop Nest Optimization
Dependence Analysis
Parallelization
Loop transformations (fission, fusion, interchange, peeling, tiling, unroll & jam)
Array privatization

Classic Compilers

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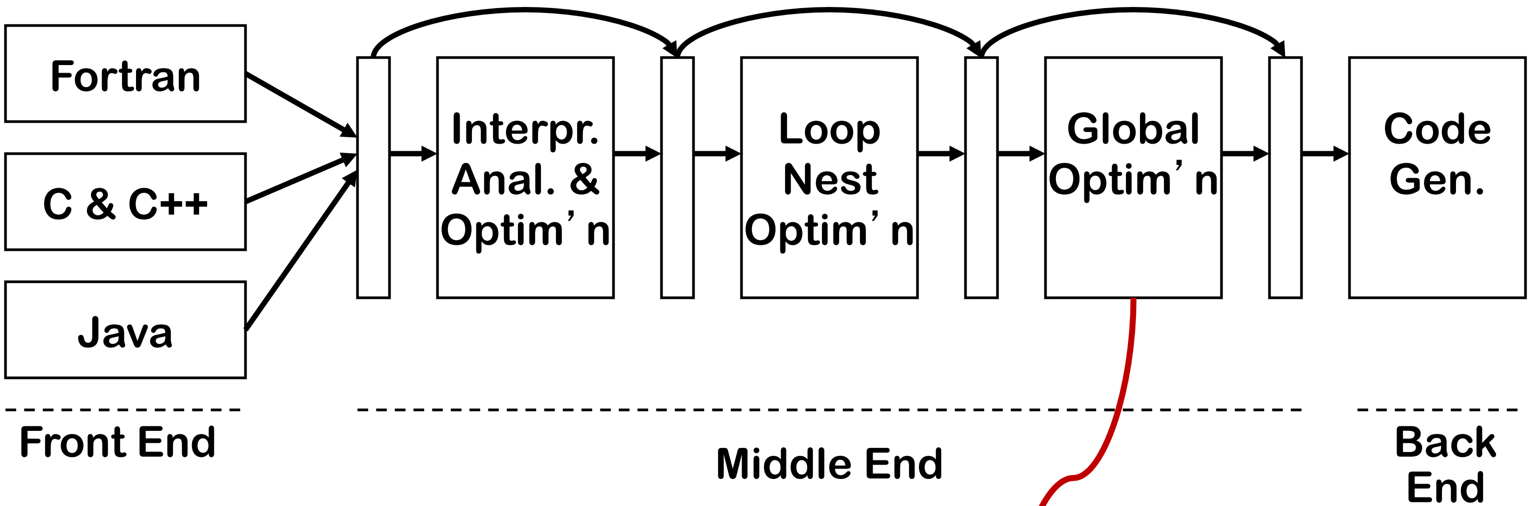

Open source optimizing compiler for IA 64

- 3 front ends, 1 back end
- Five-levels of IR
- Gradual lowering of abstraction level

Global Optimization
SSA-based analysis & opt'n
Constant propagation, PRE, OSR+LFTR, DVNT, DCE
(also used by other phases)

Classic Compilers

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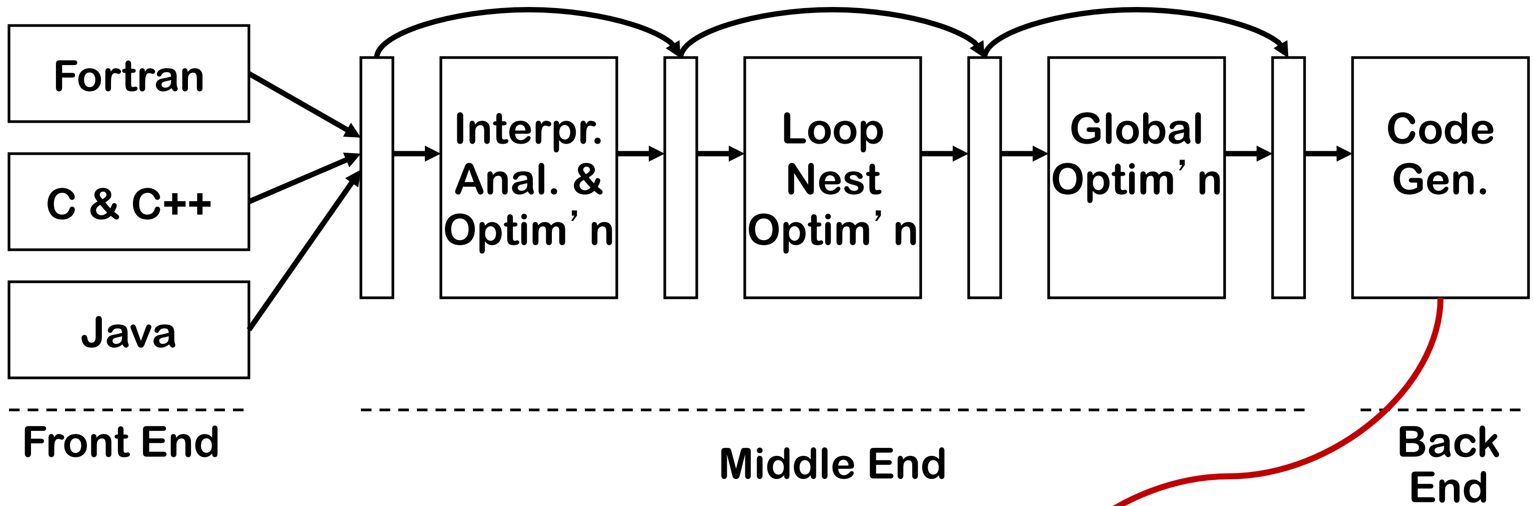


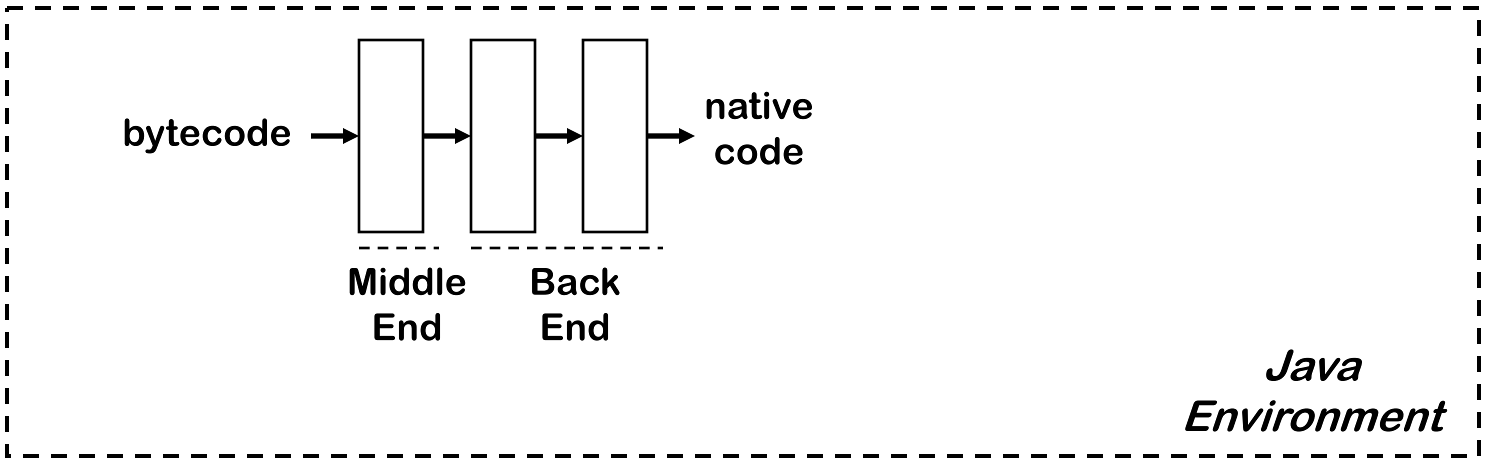
Open source optimizing compiler for IA 64

- 3 front ends, 1 back end
- Five-levels of IR
- Gradual lowering of abstraction level

Code Generation
If conversion & predication
Code motion
Scheduling (inc. sw pipelining)
Allocation
Peephole optimization

Classic Compilers

Even a 2000 JIT fits the mold, albeit with fewer passes



- Front End tasks are handled elsewhere
- Few (if any) optimizations

  Avoid expensive analysis

  Emphasis on generating native code

  Compilation must be profitable

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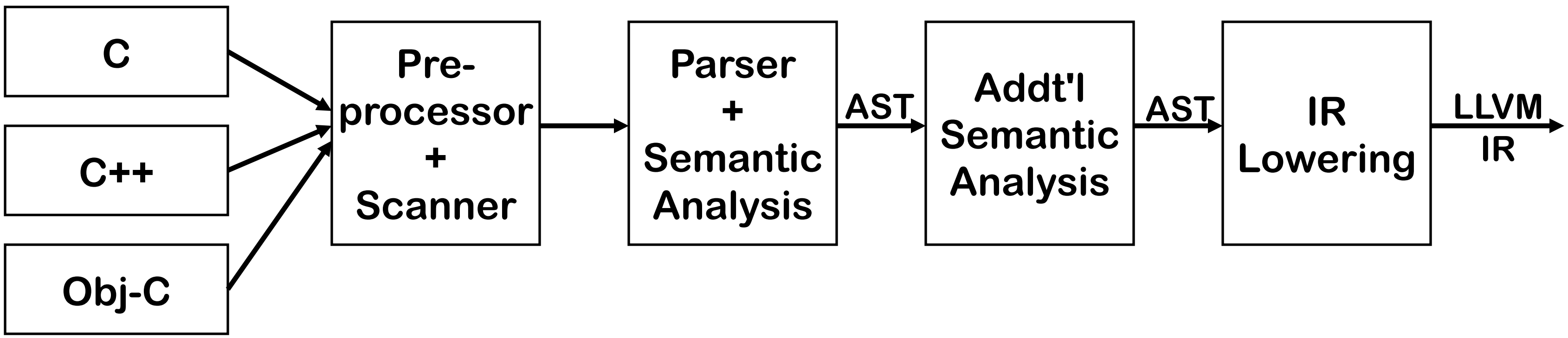
A Modern Compiler

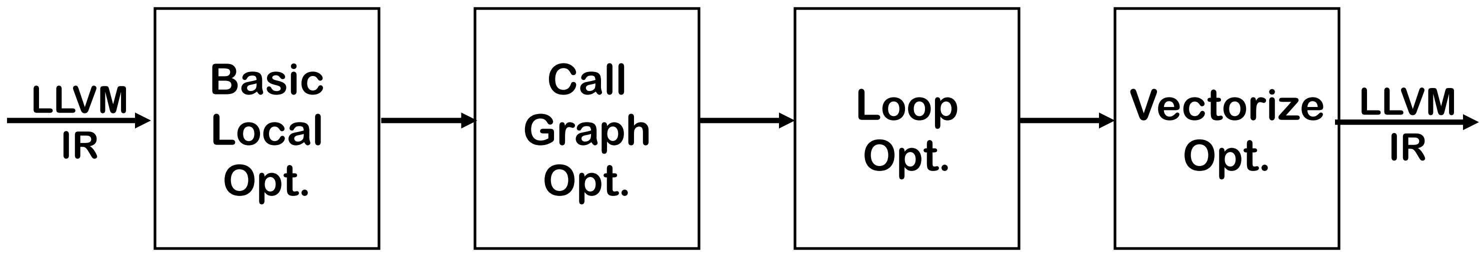
2014: Clang (LLVM) Compiler System – *Front End*



- Clang – C Language Front End for LLVM compiler infrastructure (default C/C++ compiler on Mac OS X and FreeBSD)
- Parser is *recursive descent* (top down), and most semantic analysis is completed at parse time
- *Lowering* process converts the higher-level IR (AST) into the lower-level IR (LLVM IR)

A Modern Compiler

2014: Clang (LLVM) Compiler System – *Optimizer*

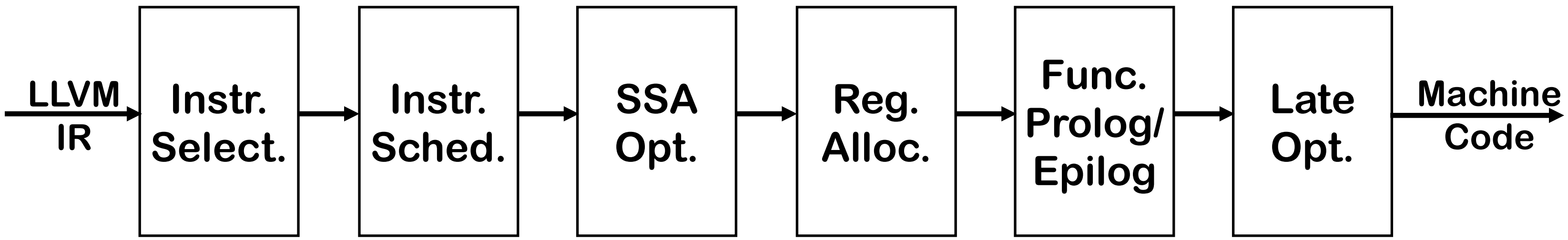


- LLVM includes ~100 optimization passes – this is (approximately) the default grouping of passes with the -O2 compiler flag
- Some passes are repeated multiple times (like simplify CFG)

- Basic local – memory promotion, dead arguments, combine instructions
- Call graph – Remove dead functions, inline functions, etc.
- Loops – Loop invariant code, loop unrolling, loop deletion
- Vectorization – Take advantage of SIMD processors

A Modern Compiler

2014: Clang (LLVM) Compiler System – *Back End*



- Back end is designed to be retargetable to new platforms without *many* changes to the earlier code, but some (like function ABI) requires changes to Clang codebase
- SSA – LLVM IR uses *static single assignment* (covered later)
- Some optimizations still happen in the back end

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Summary

- Overview of a Compiler's Tasks
  - Basic Translation from High-level to Instruction level
- Structure of a "Classical" Compiler
  - Traditional Three Phase Structure
- Classical Compilers
  - Static vs. Dynamic