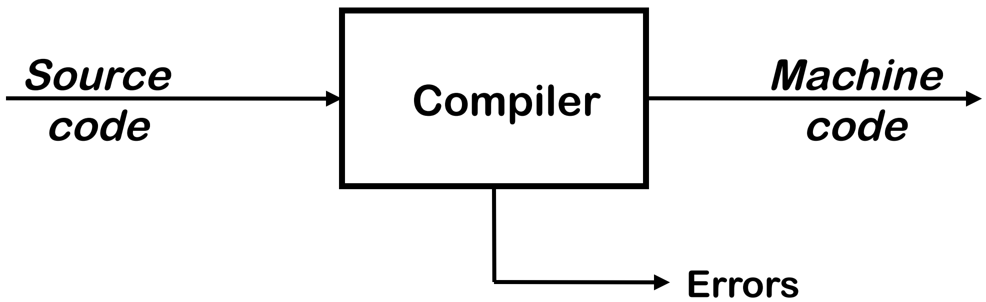
The View from 35,000 Feet

High-level View of a Compiler

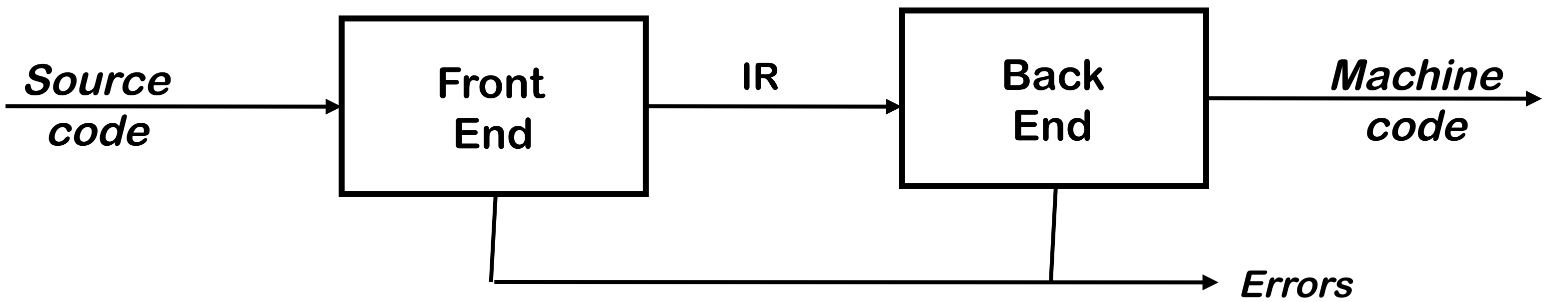


Implications

- 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

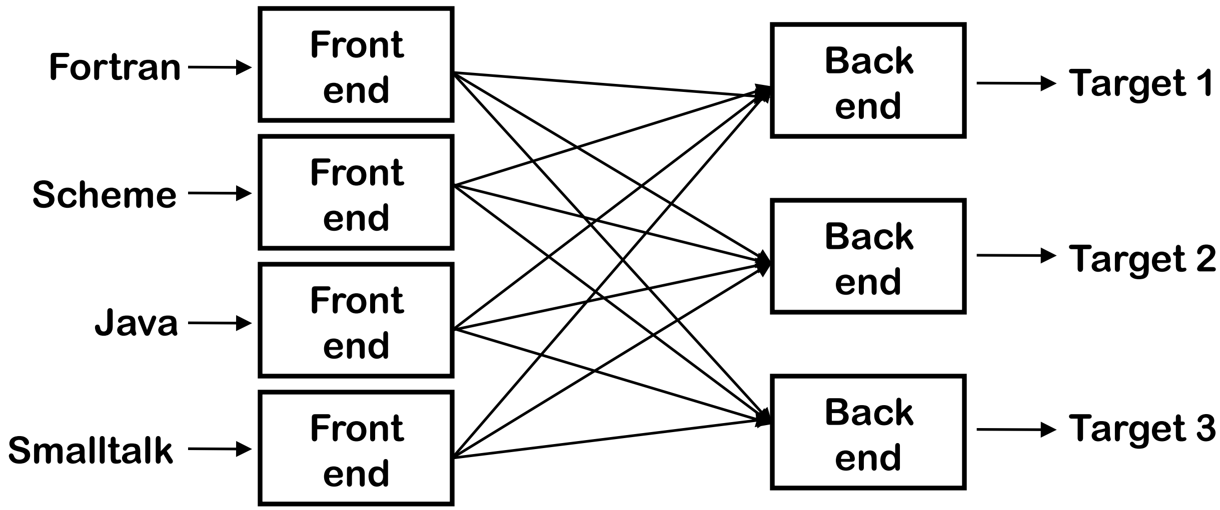


Implications

- 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

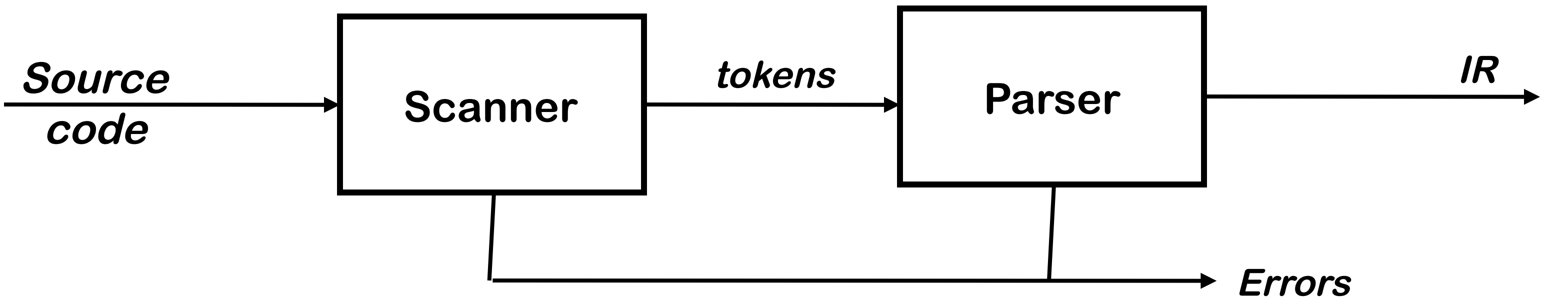


Can we build *n x m* compilers with *n+m* components?

- 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

Limited success in systems with very low-level IRs

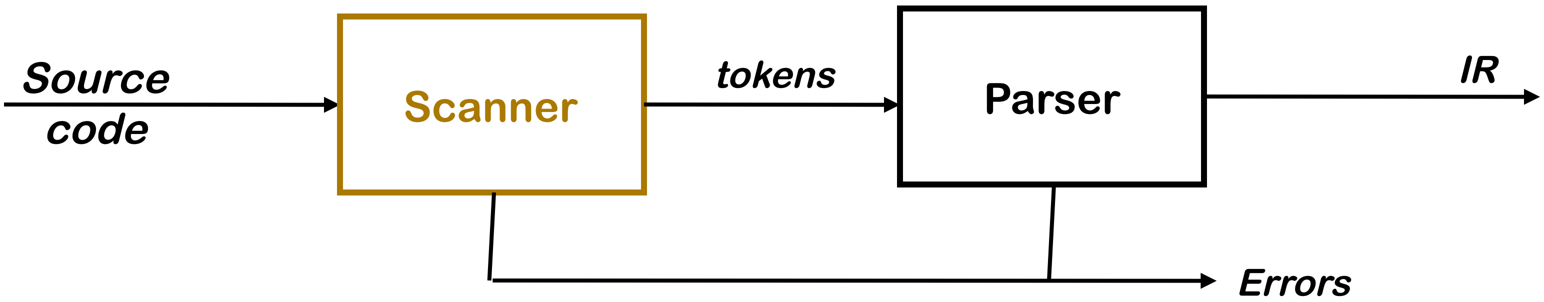
The Front End



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

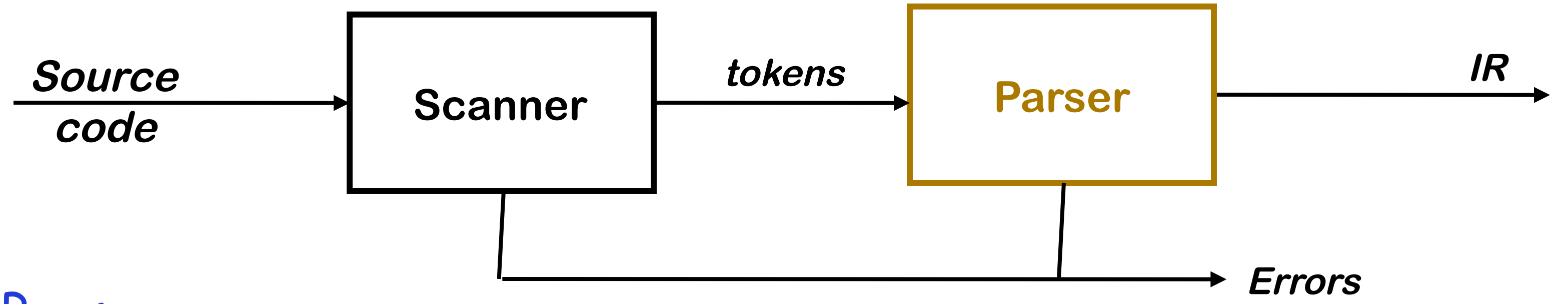
The Front End



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

Hand-coded parsers are fairly easy to build

Most books advocate using automatic parser generators

The Front End

Context-free syntax is specified with a grammar

$$SheepNoise \rightarrow \underline{baa}\ SheepNoise \mid \underline{baa}$$

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* $(P : N \rightarrow N \cup T)$

(Example due to Dr. Scott K. Warren)

The Front End

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}

Context-free syntax can be put to better use

- 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 ***CFG***

The Front End

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

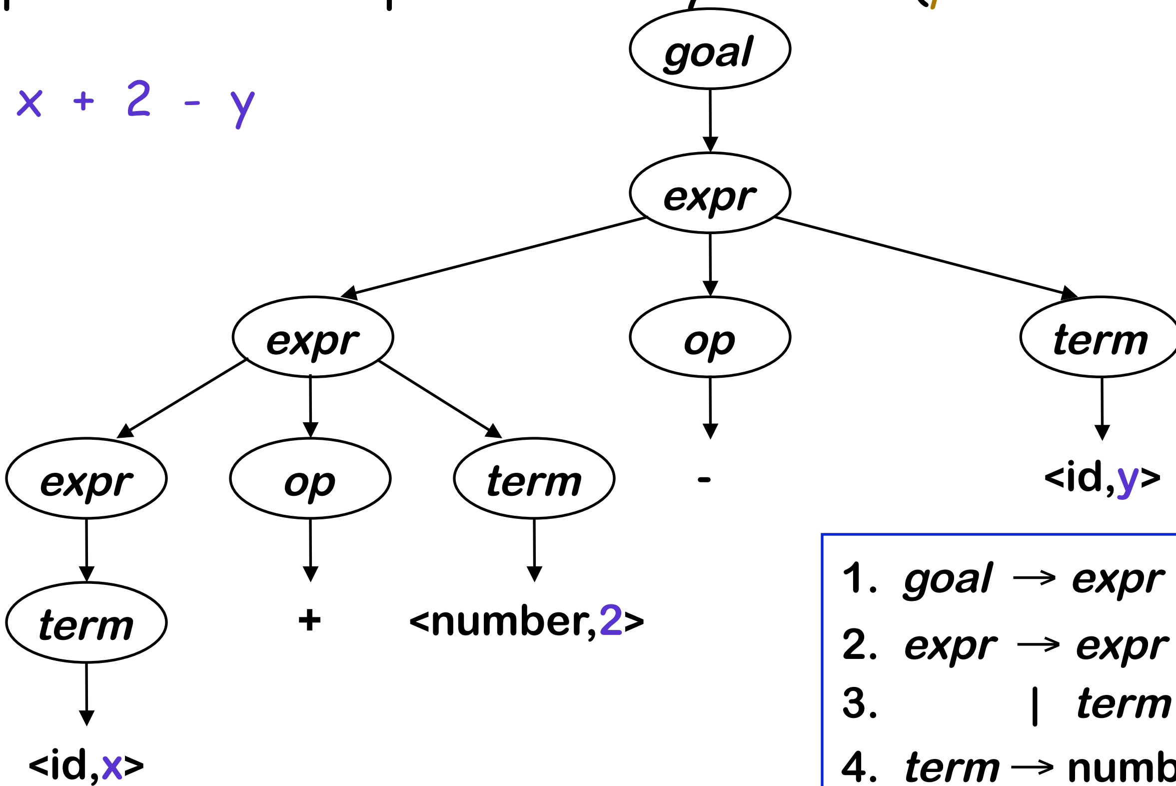
Production	Result
	goal
1	*expr*
2	*expr op term*
5	*expr op* y
7	*expr* - y
2	*expr op term* - y
4	*expr op* 2 - y
6	*expr* + 2 - y
3	*term* + 2 - y
5	x + 2 - y

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



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2. *expr* → *expr op term*
3. | *term*
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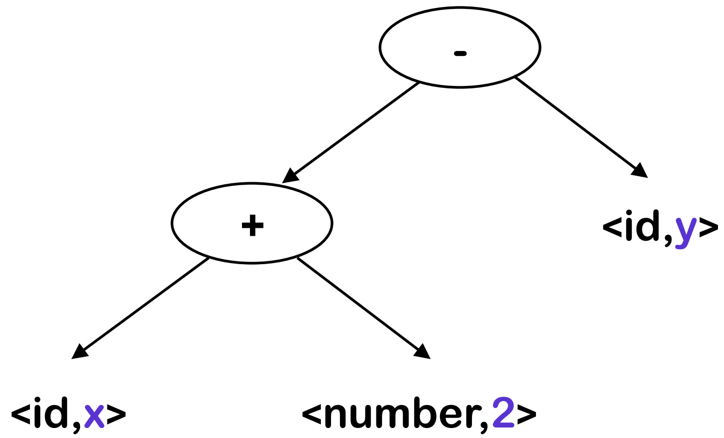
7. | -

This contains a lot of unneeded information.

The Front End

Compilers often use an *abstract syntax tree*

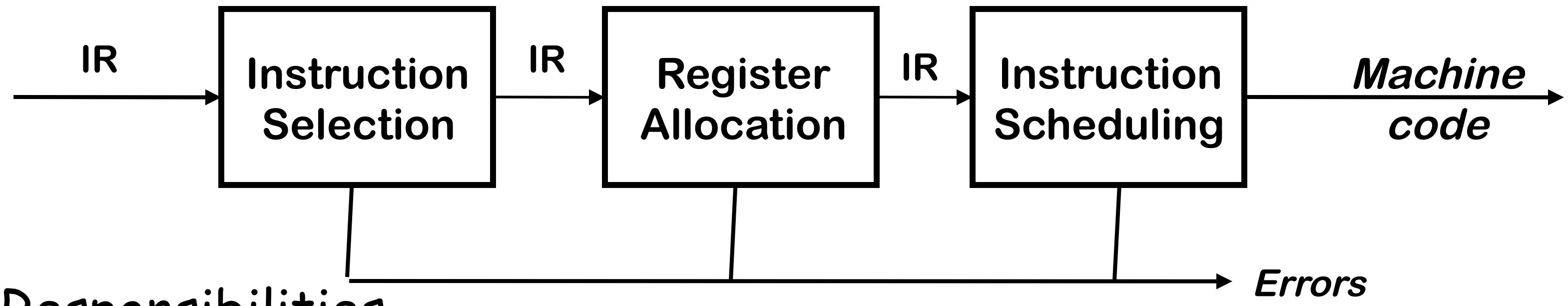


The AST summarizes grammatical structure, without including detail about the derivation

This is much more concise

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

The Back End

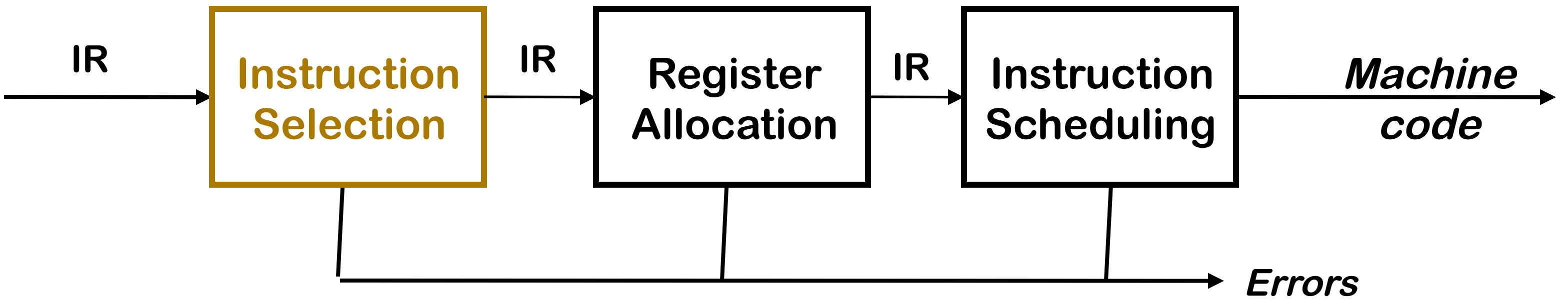


Responsibilities

- 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



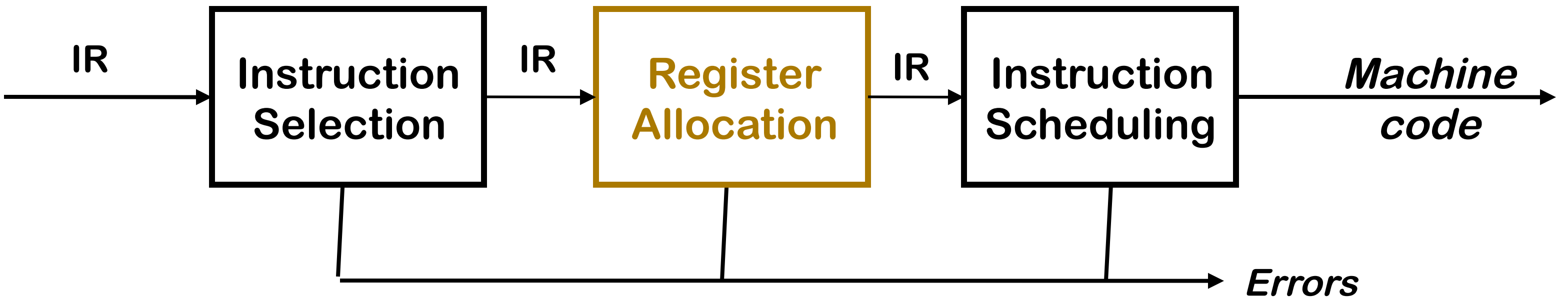
Instruction Selection

- 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

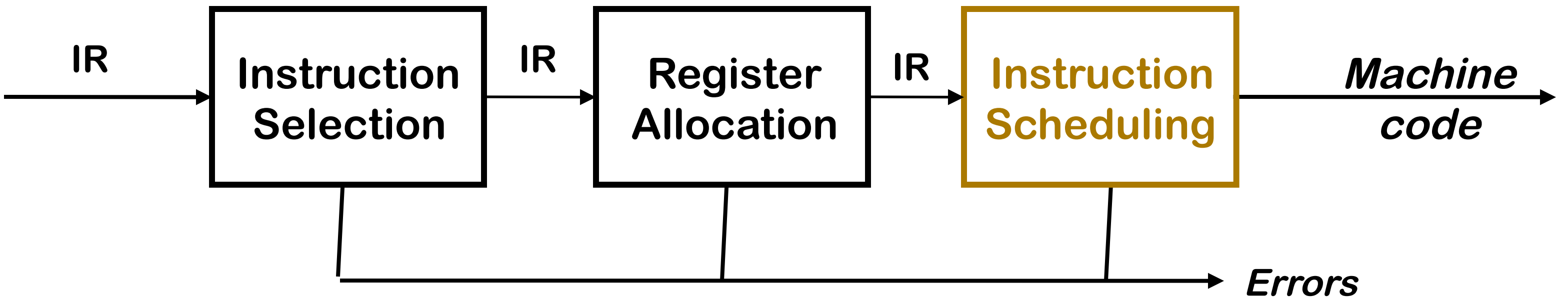


Register Allocation

- 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



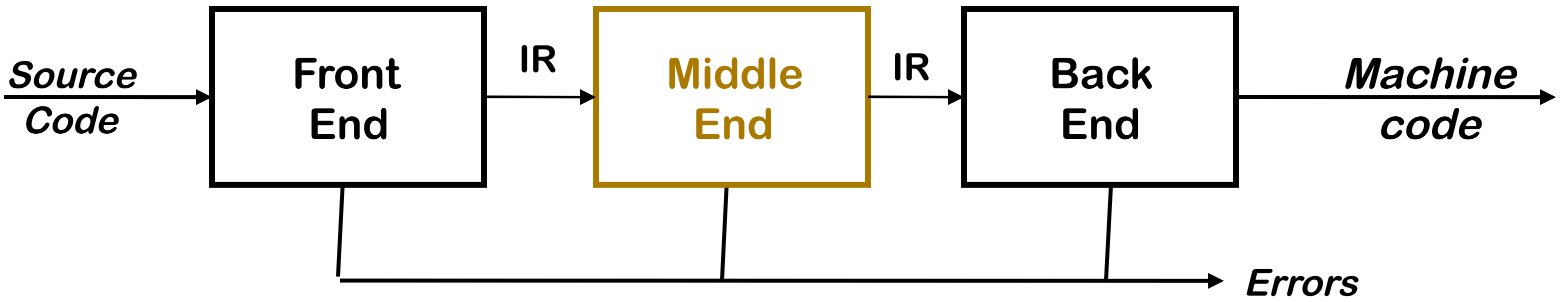
Instruction Scheduling

- 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

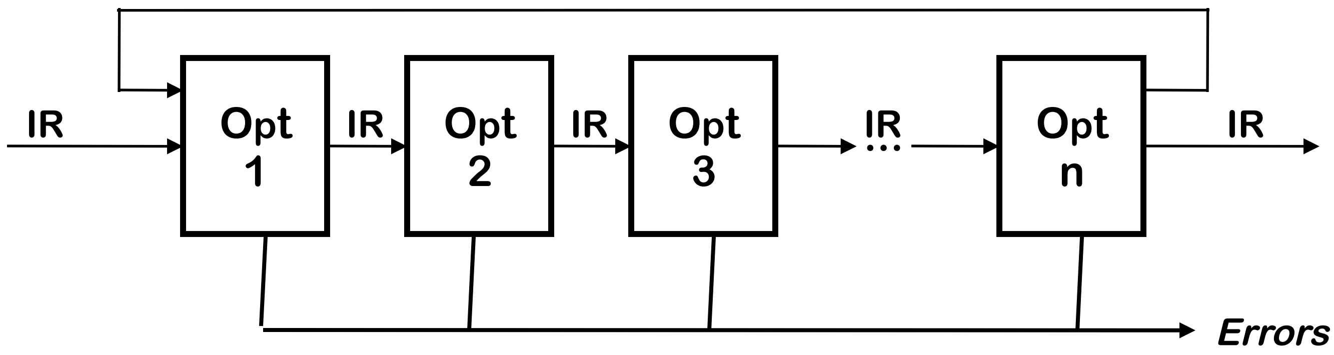
Traditional Three-pass Compiler



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

Example

- Optimization of Subscript Expressions in Fortran

Address(A(I,J)) = address(A(0,0)) + J * (column size) + I

Does the user realize a multiplication is generated here?

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Does the user realize a multiplication is generated here?

```
DO I = 1, M
     A(I,J) = A(I,J) + C
ENDDO
```

Example

- Optimization of Subscript Expressions in Fortran

Address(A(I,J)) = address(A(0,0)) + J * (column size) + I

↑

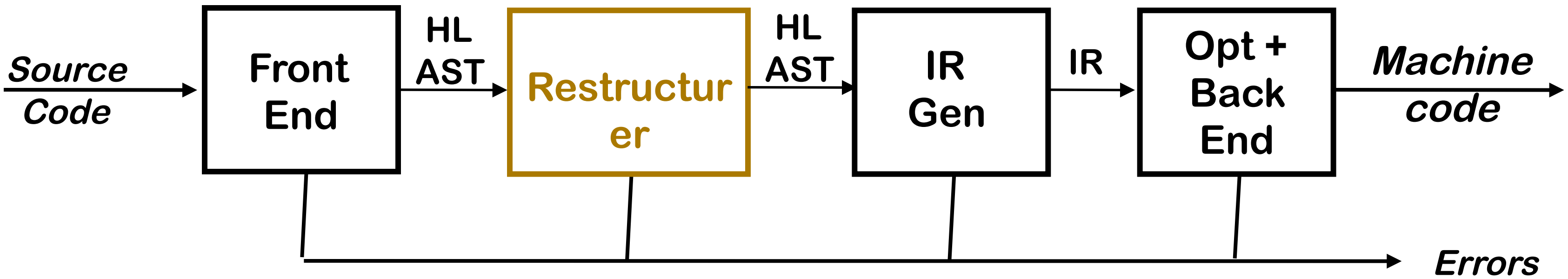
Does the user realize a multiplication is generated here?

```
DO I = 1, M
     A(I,J) = A(I,J) + C
ENDDO
```

→

```
compute addr(A(0,J))
DO I = 1, M
     add 1 to get addr(A(I,J))
     A(I,J) = A(I,J) + C
ENDDO
```

Modern Restructuring Compiler



Typical Restructuring Transformations:

- Blocking for memory hierarchy and register reuse
- Vectorization
- Parallelization
- All based on dependence
- Also full and partial inlining

Subject of CISC 673

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

Lab Zero

- Implement two COOL programs 100-200 lines each
- Material on the web
  - Lab Assignment, Cool Manual
- Specs for Lab 0 available on Web
  - Due in one week (9/16)
    - Speak to me after class if you will need more time
  - Practice with COOL and simulator available
  - Grading will be done by TA
    - You will meet with TA to deliver code
- Next Class (Thursday)
  - Led by TA
  - Introduction to COOL, SVN, etc.

Next Week

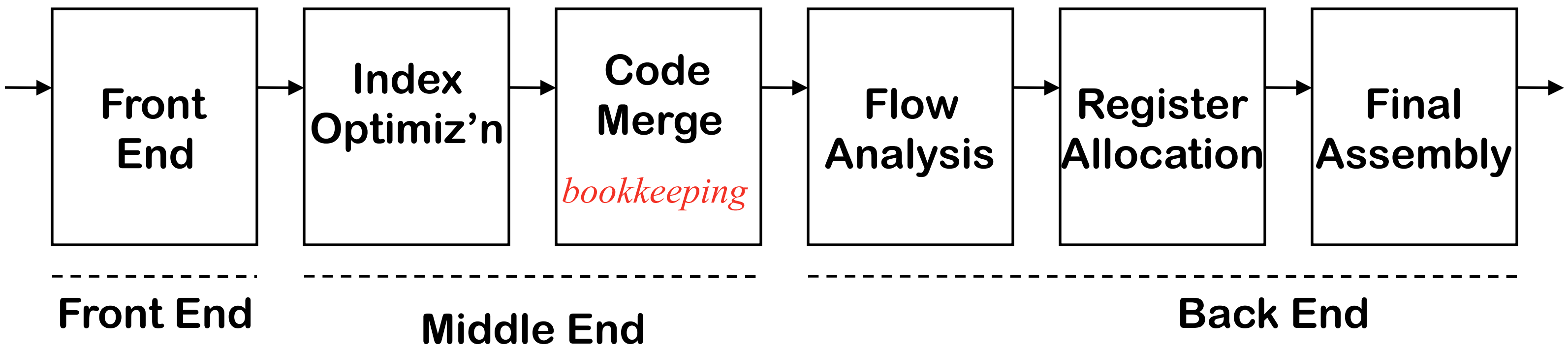
- Introduction to Scanning (aka Lexical Analysis)
- Material is in Chapter 2

- Specs for Lab 1 available next Tuesday (9/16)

Extra Slides Start Here

Classic Compilers

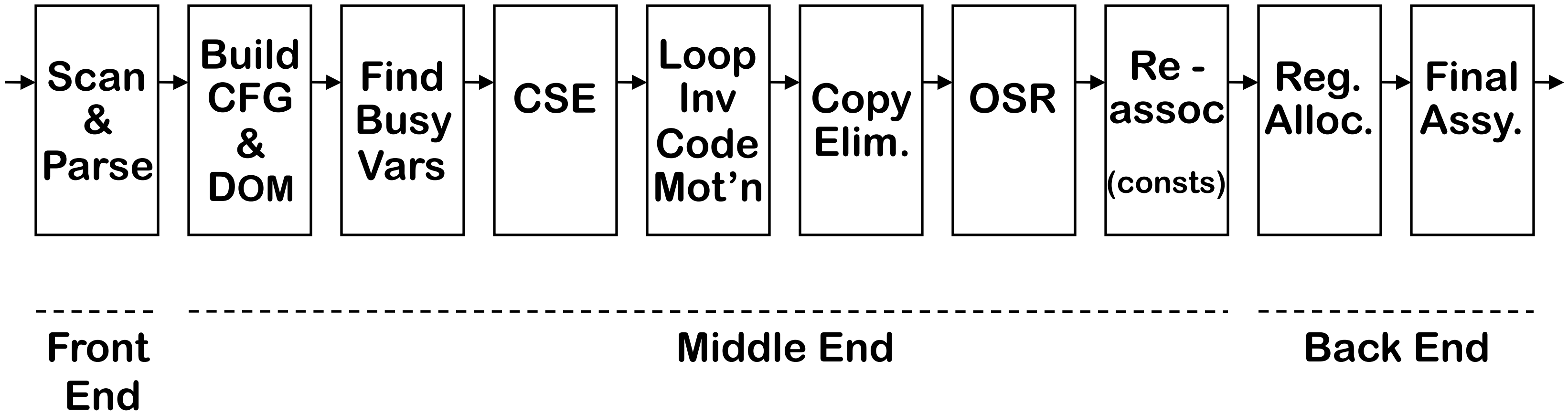
1957: The FORTRAN Automatic Coding System



- 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

Classic Compilers

1969: IBM's FORTRAN H Compiler



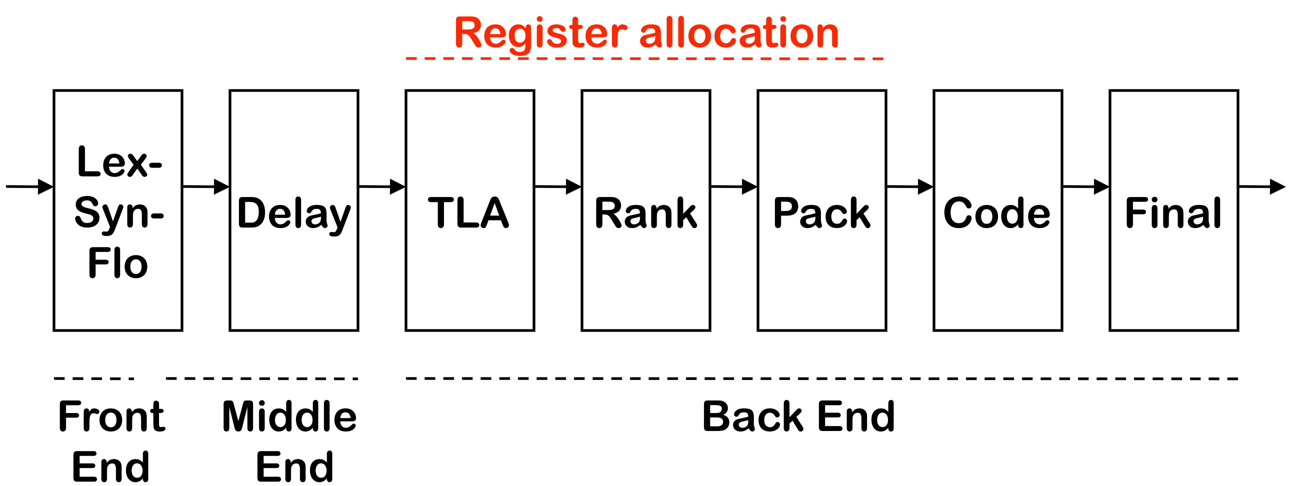
- Used low-level IR (quads), identified loops with dominators
- Focused on optimizing loops ("inside out" order)

  Passes are familiar today

- Simple front end, simple back end for IBM 370

Classic Compilers

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

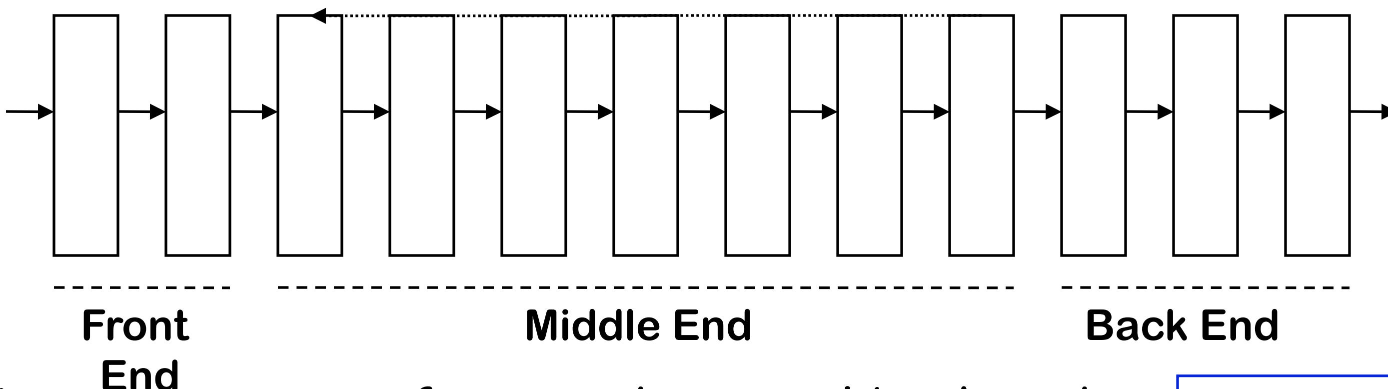


- The great compiler for the PDP-11
- Seven passes in a fixed order
- Focused on code shape & instruction selection
  - LexSynFlo did preliminary flow analysis
  - Final included a grab-bag of peephole optimizations

Basis for early VAX & Tartan Labs compilers

Classic Compilers

1980: IBM's PL.8 Compiler



- Many passes, one 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

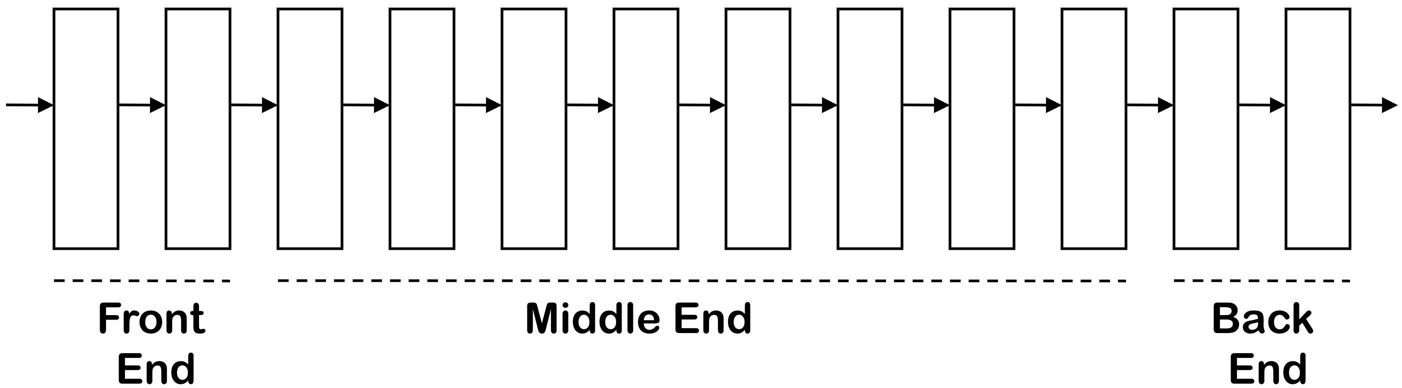
Dead code elimination
Global CSE
Code motion
Constant folding
Strength reduction
Value numbering
Dead store elimination
Code straightening
Trap elimination
Algebraic reassociation

Multi-level IR has become common wisdom

*

Classic Compilers

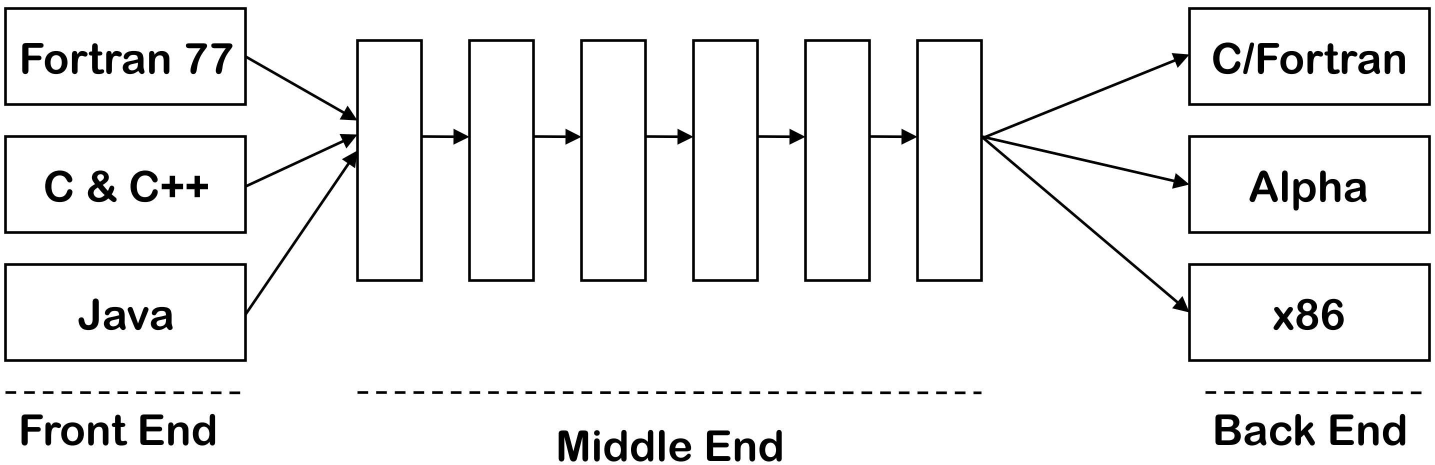
1986: HP's PA-RISC Compiler



- 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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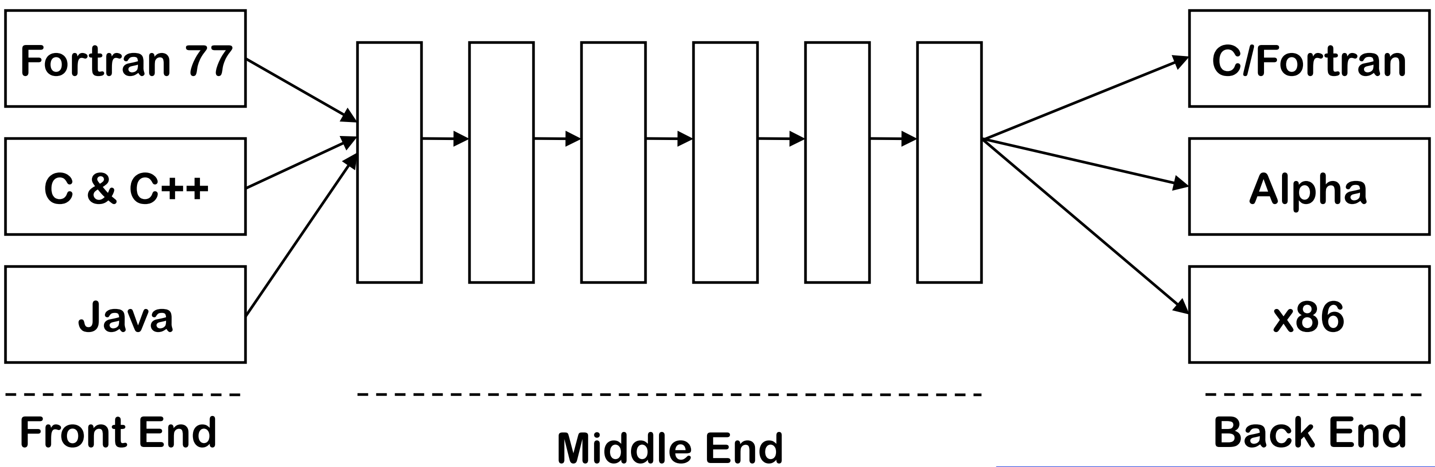

Another classically-built compiler

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

Classic Compilers

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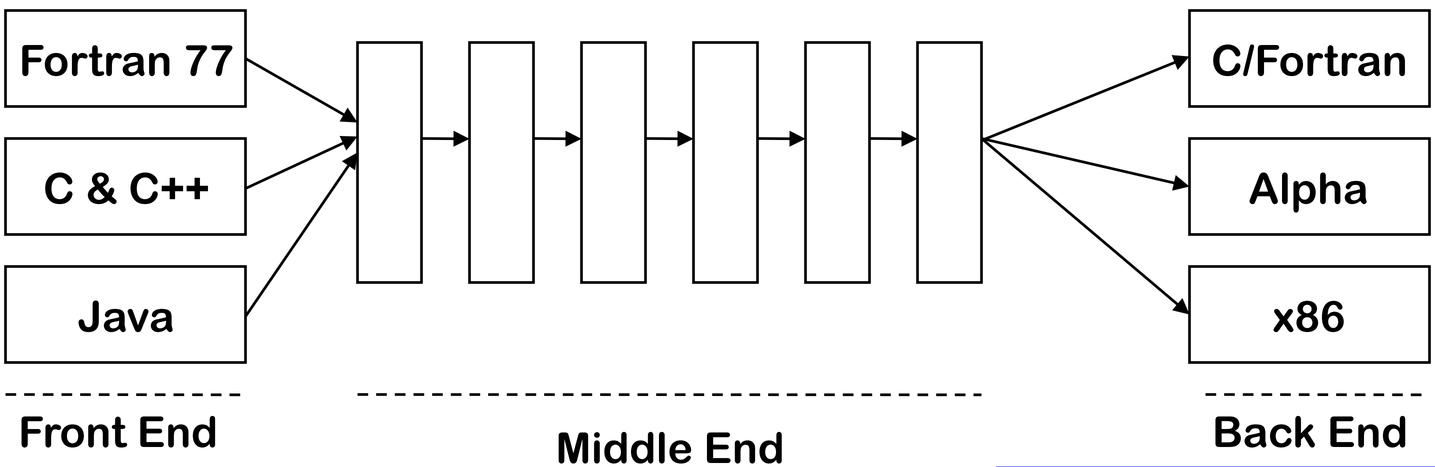

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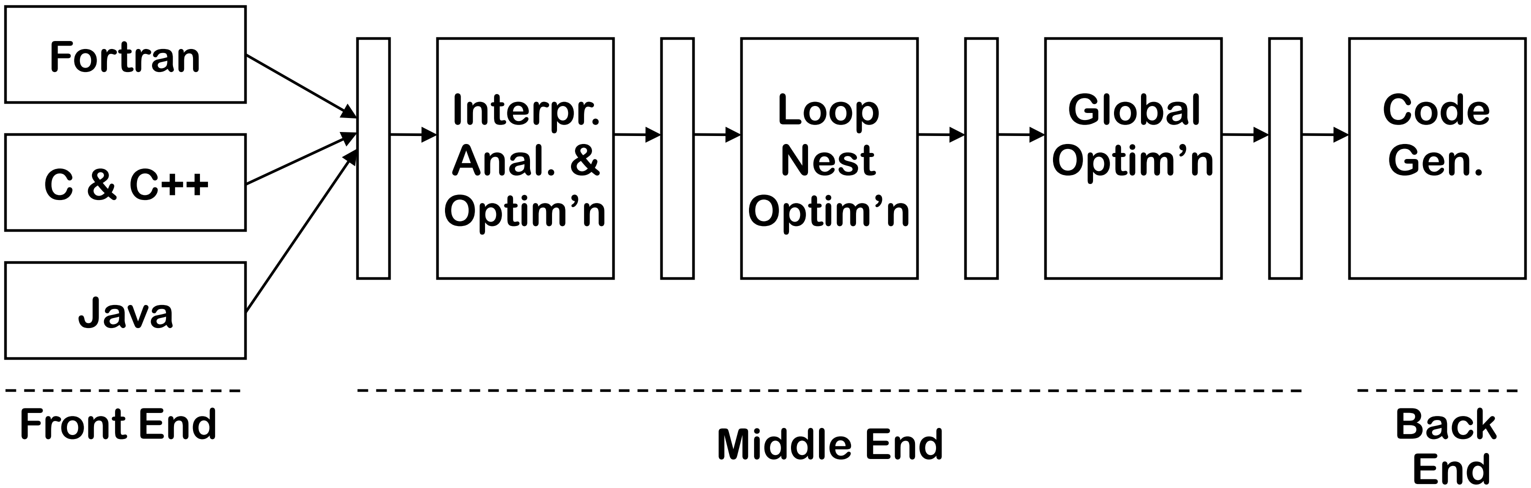
Data dependence analysis
Scalar & array privitization
Reduction recognition
Pointer analysis
Affine loop transformations
Blocking
Capturing object definitions
Virtual function call elimination
Garbage collection

Classic Compilers

2000: The SGI Pro64 Compiler (now Open64 from UDEL ECE)



Open source optimizing compiler for IA 64

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

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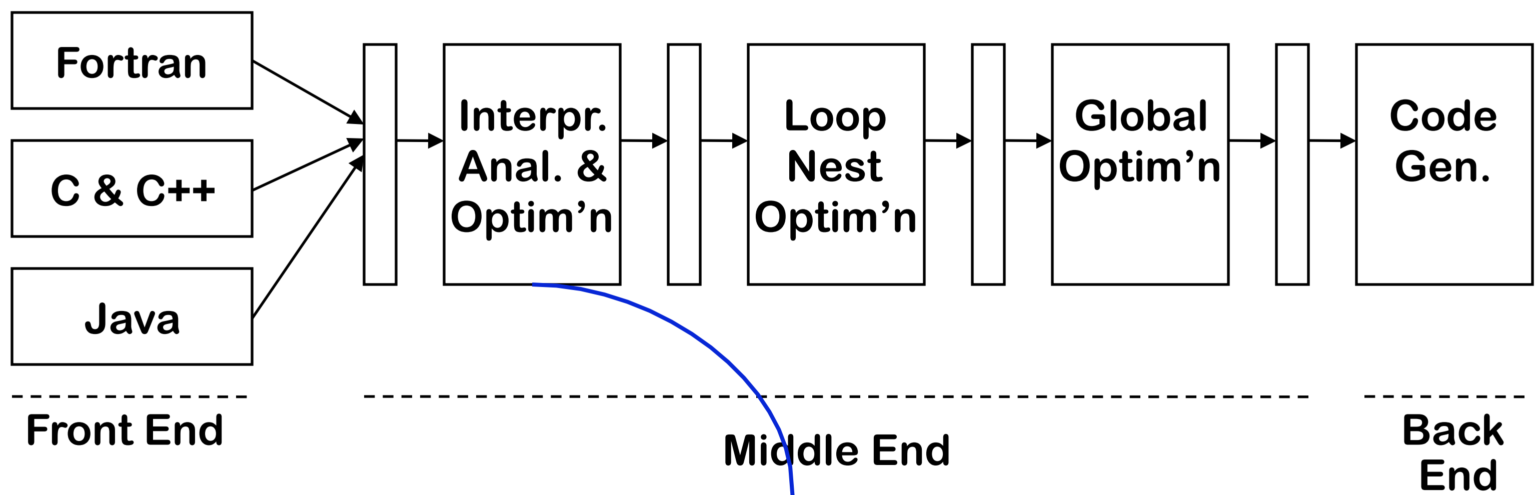

Interprocedural
Classic analysis
Inlining (user & library code)
Cloning (constants & locality)
Dead function elimination
Dead variable elimination

Open source optimizing compiler for IA 64

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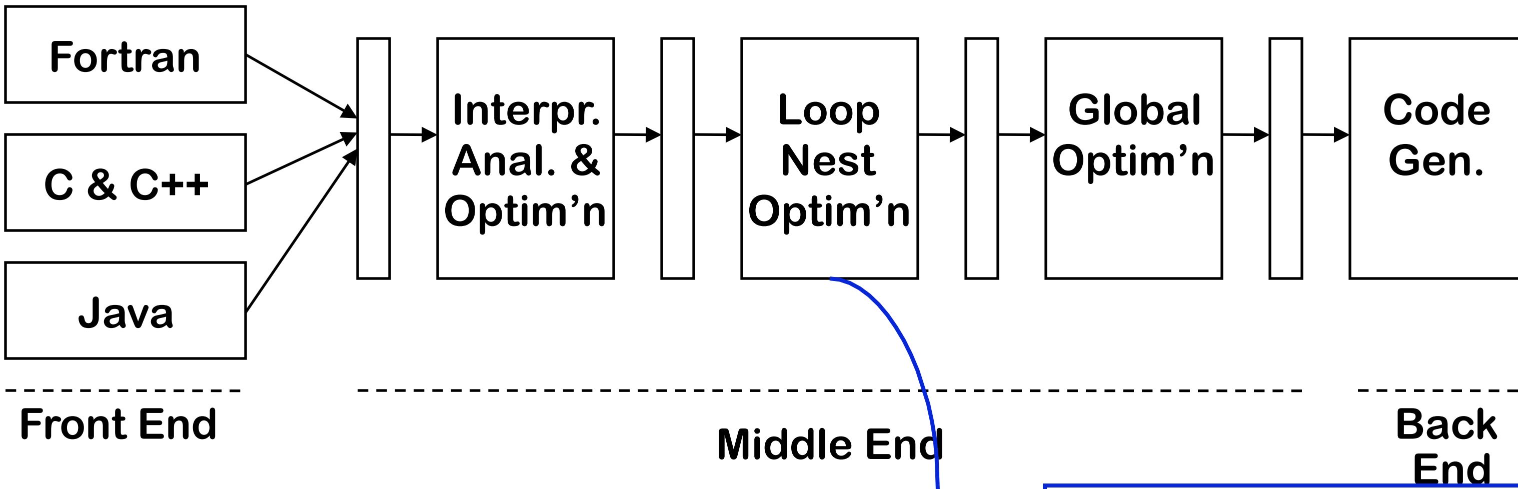

Loop Nest Optimization
Dependence analysis
Parallelization
Loop transformations (fission, fusion, interchange, peeling, tiling, unroll & jam)
Array privitization

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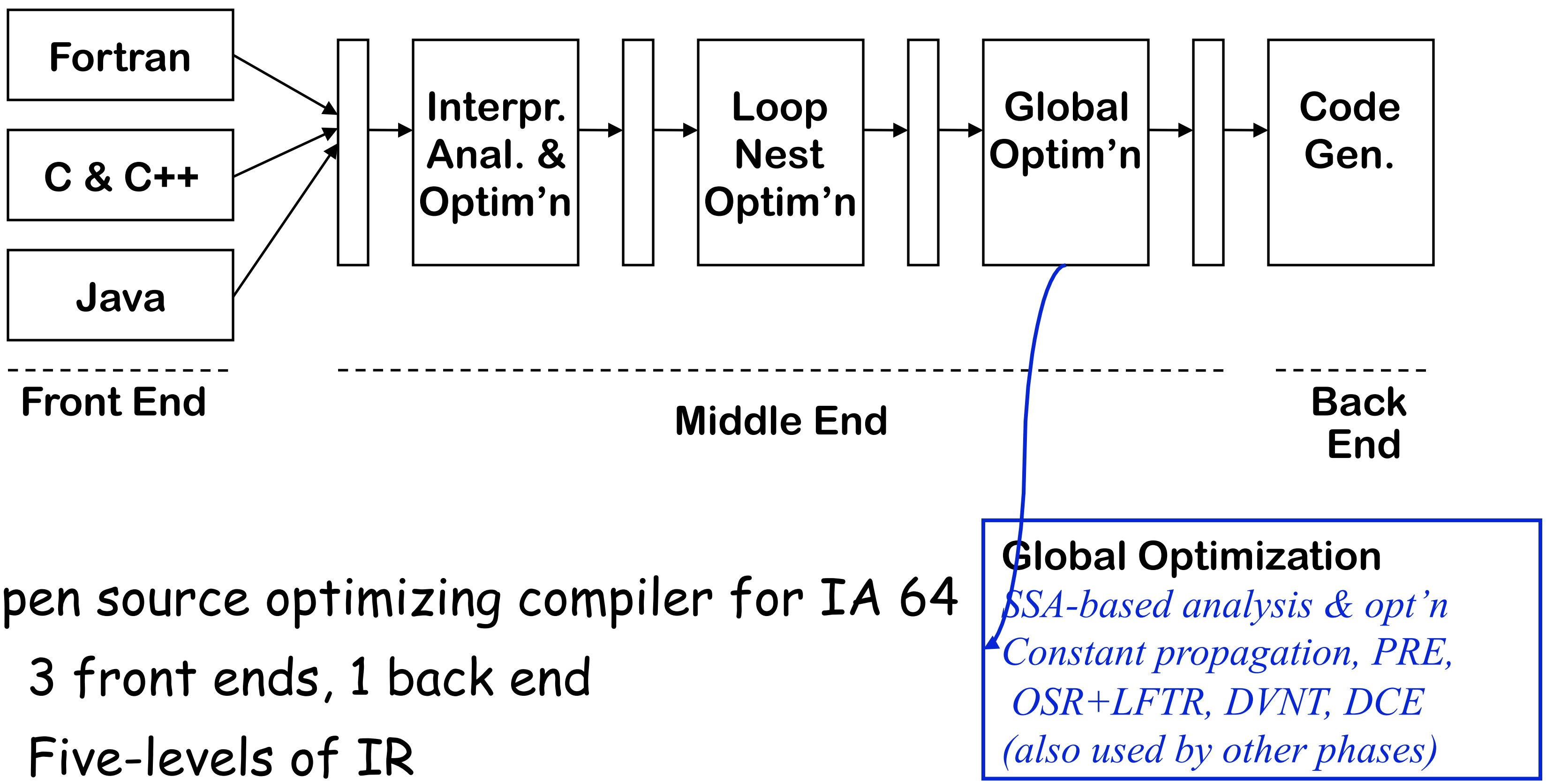

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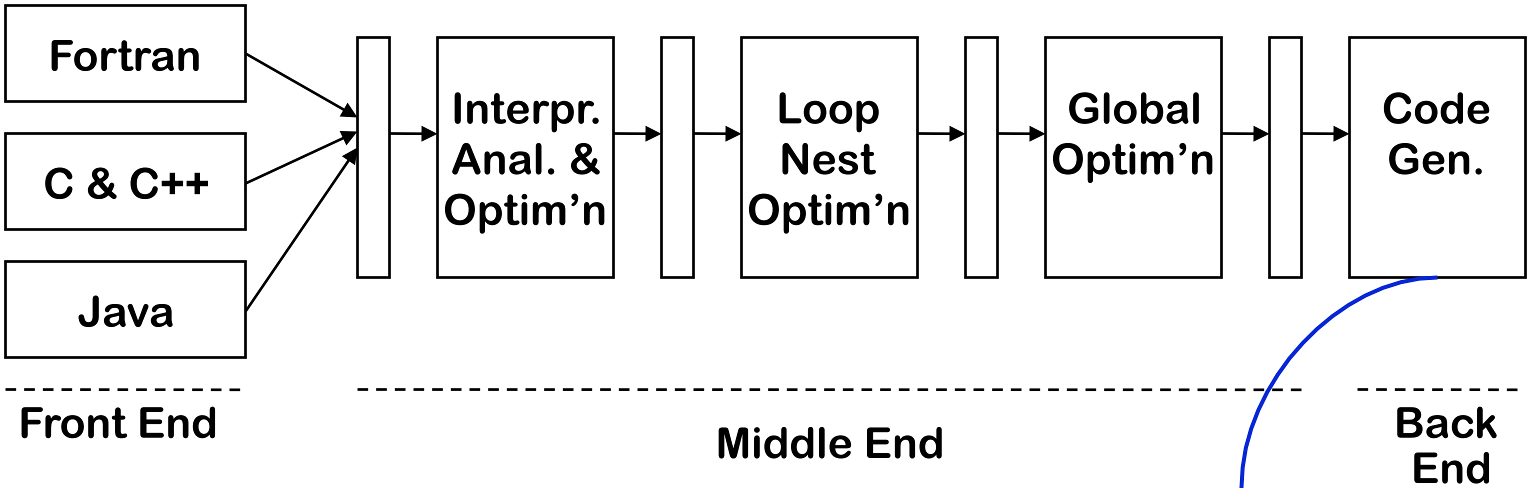


Code Generation

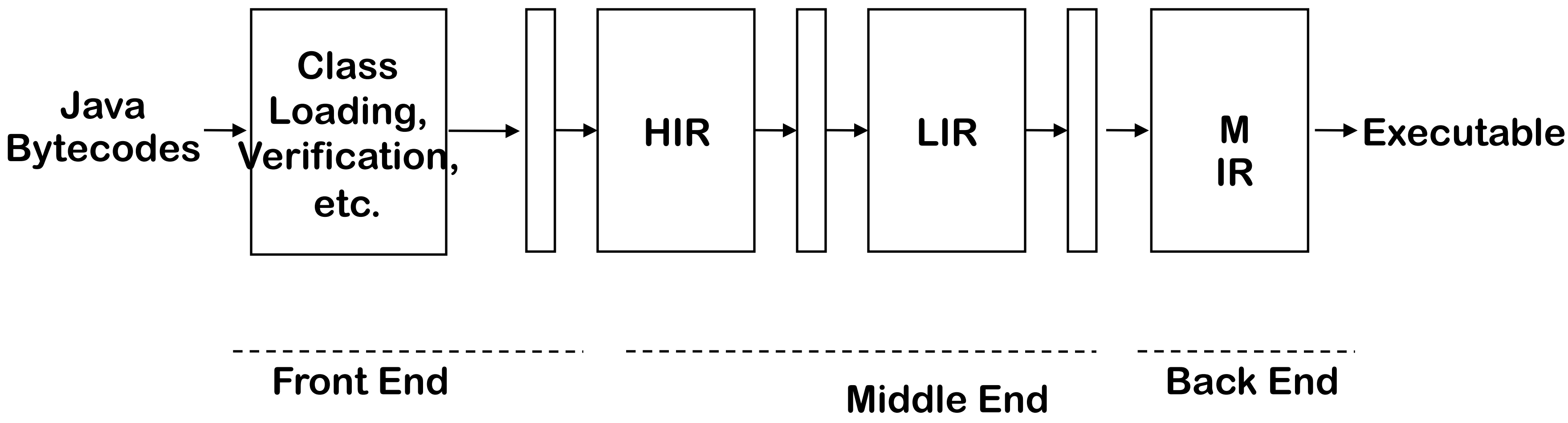
If conversion & predication
Code motion
Scheduling (inc. sw pipelining)
Allocation
Peephole optimization

Open source optimizing compiler for IA 64

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

Classic Compilers

Even a 2007 Java JIT fits the mold, e.g., JIKES RVM (IBM)



- Several front end tasks are handled elsewhere
- "Hot-spot" Optimizer
  - Avoid expensive analysis at first
  - Compilation must be profitable

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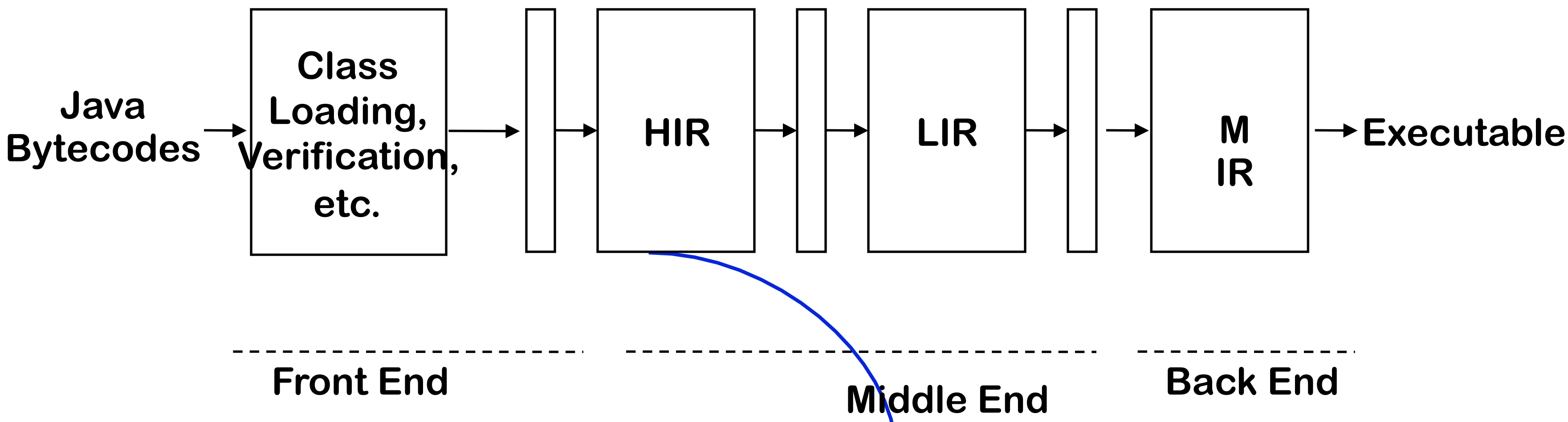

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HIR Optimizations
Tail Recursion
Escape Analysis
Load Elimination
Loop Unrolling

Classic Compilers

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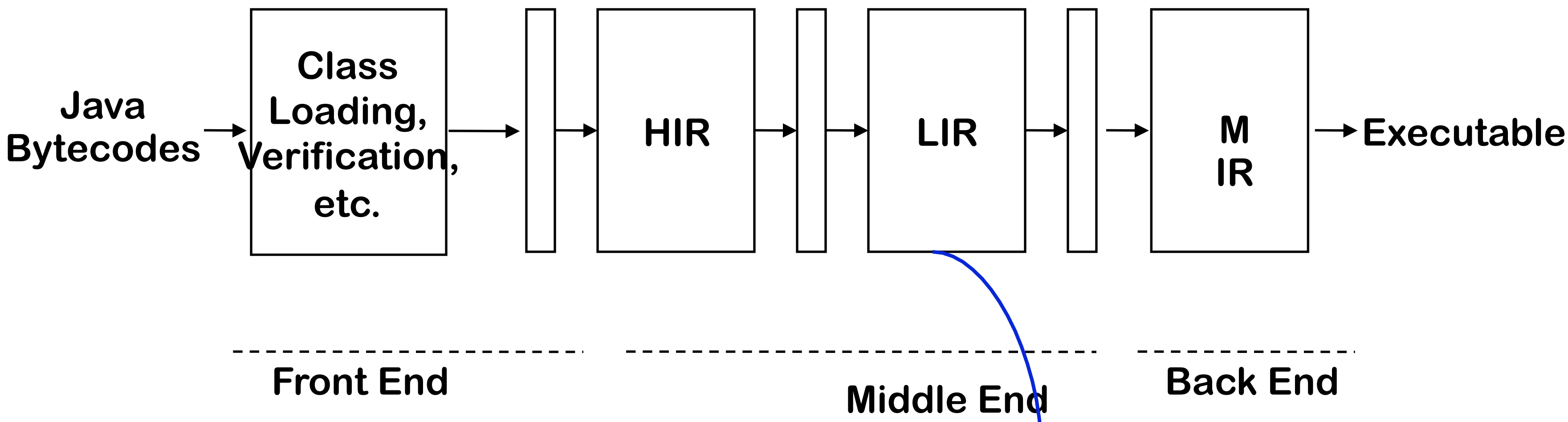

- Several front end tasks are handled elsewhere
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  Avoid expensive analysis at first

  Compilation must be profitable

LIR Optimizations

Constant Propagation
Copy Propagation
Constant Sub Elimination
Basic Block Reordering

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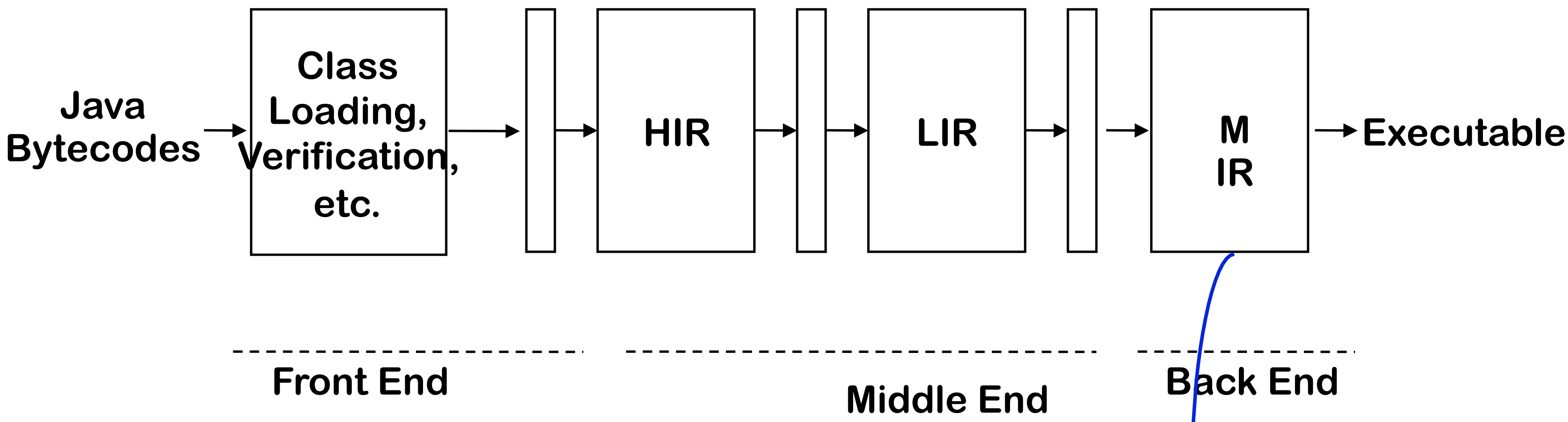

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MIR Optimizations (Code Generation)

Live Analysis
Instruction Scheduling
Register Allocation