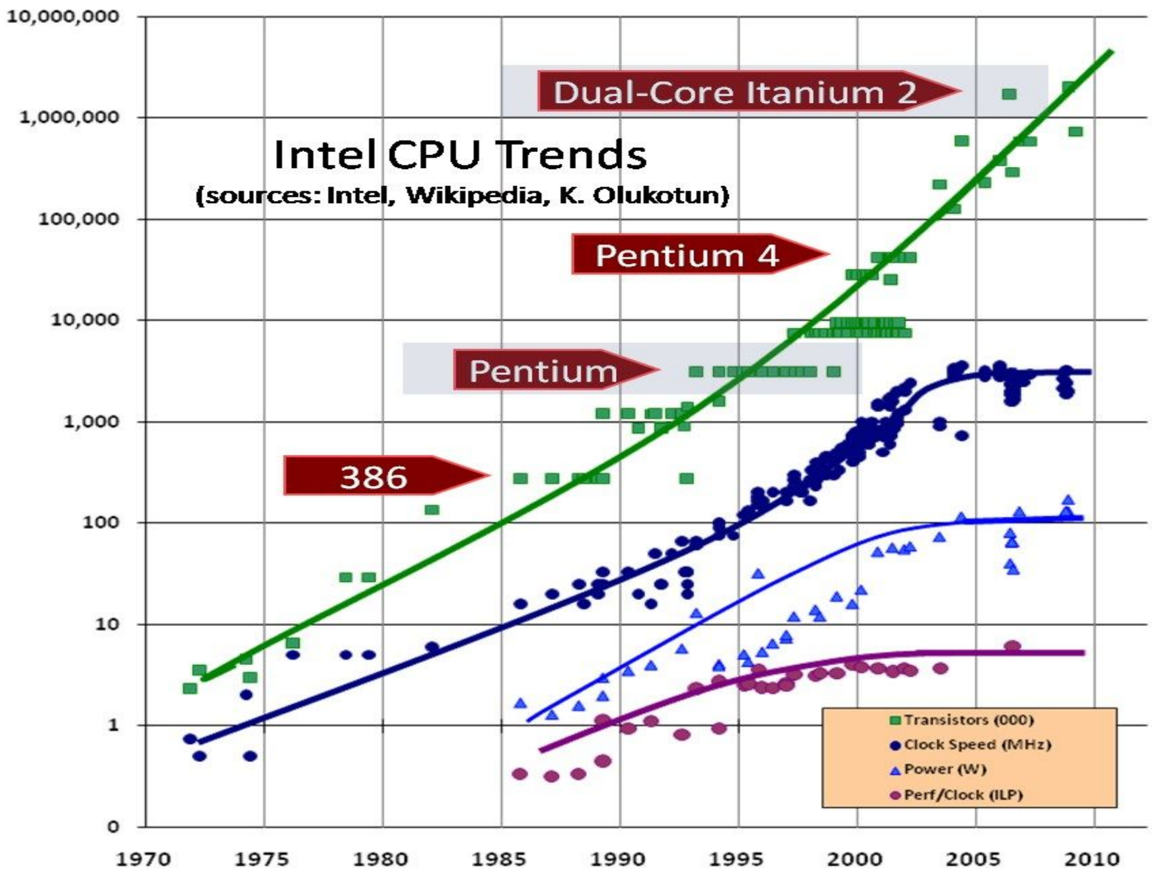
The View from 35,000 Feet
CPEN 400P – Lecture 1
Karthik Pattabiraman

Learning Objectives

- **Identify the reasons why we study compiler design**
- List the components of a traditional 2-pass compiler/3-pass and their functionality
- Provide a brief summary of the history of compilers and the state of the art today

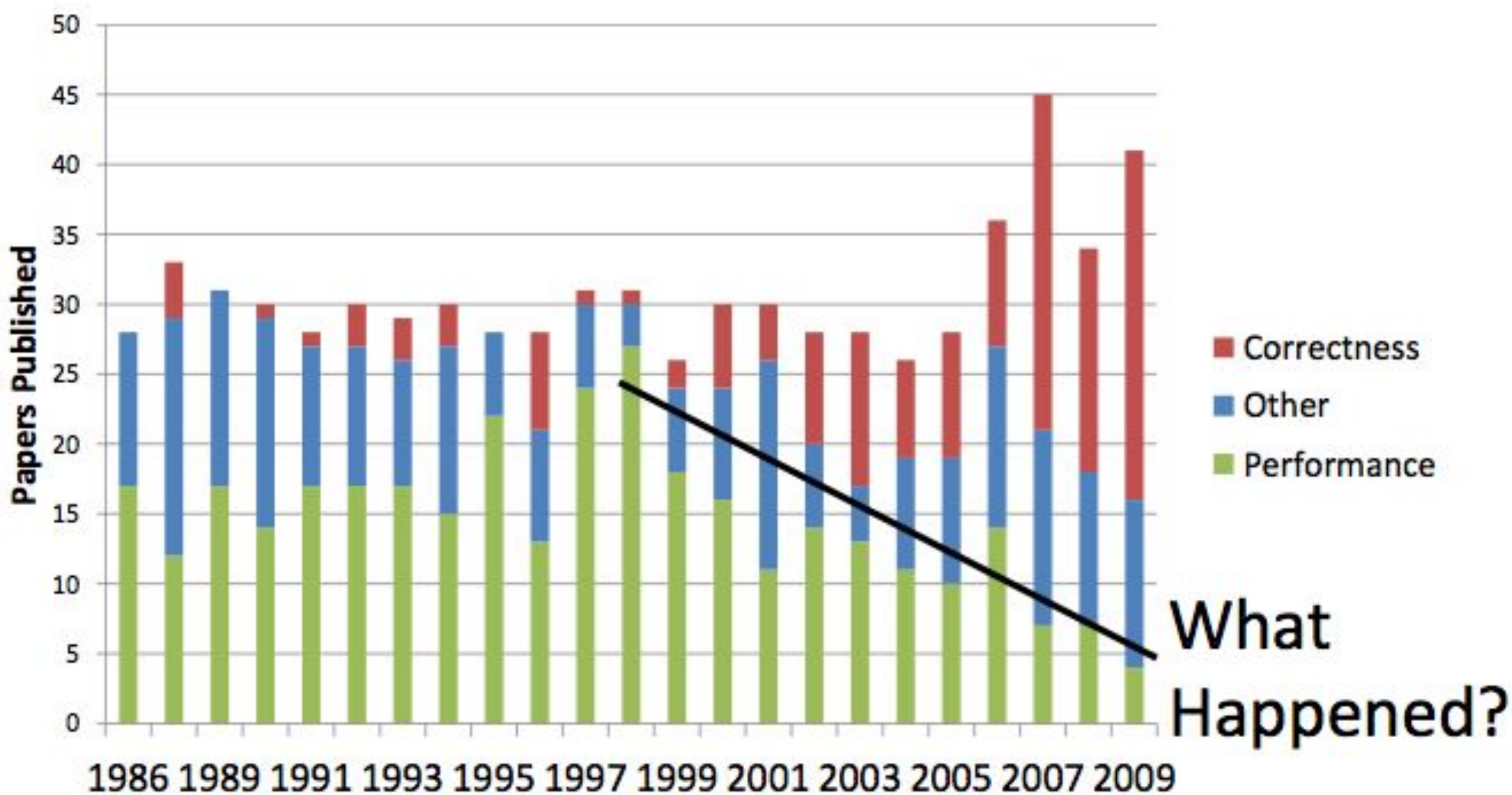
Why study compilers - 1

- Single core performance has plateuaed – need to extract performance through parallelism (i.e., parallel code)



Why study compilers - 2

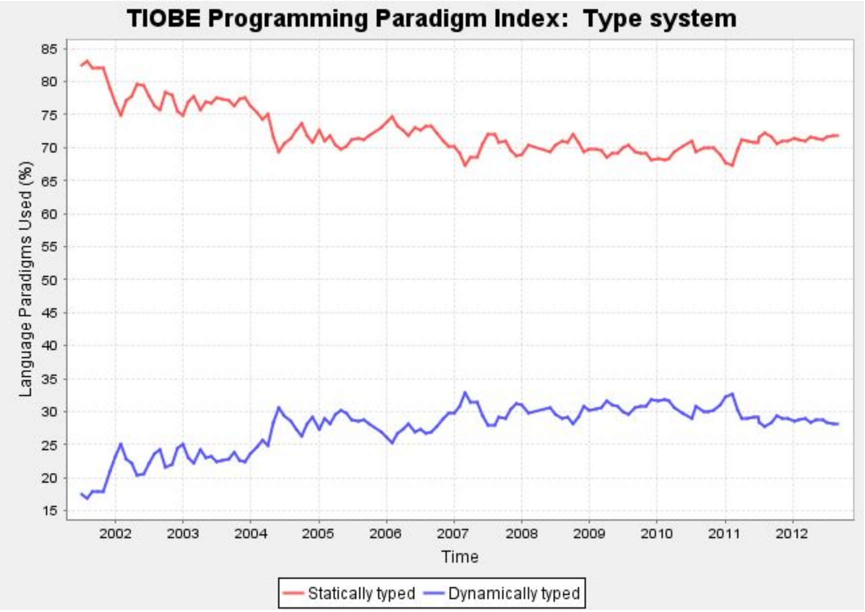
- Static analysis for reliability and security violations

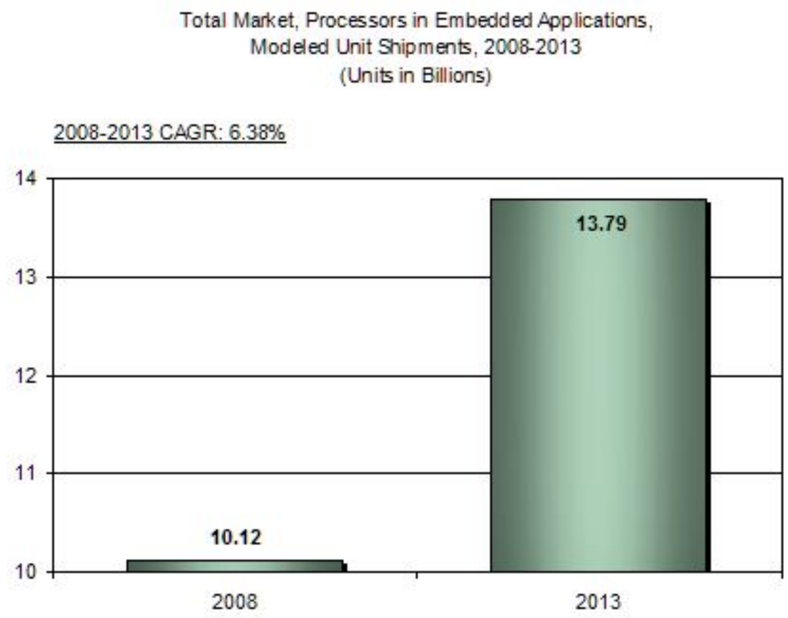


Slide courtesy: Ben Zorn, MSR

Why study compilers - 3

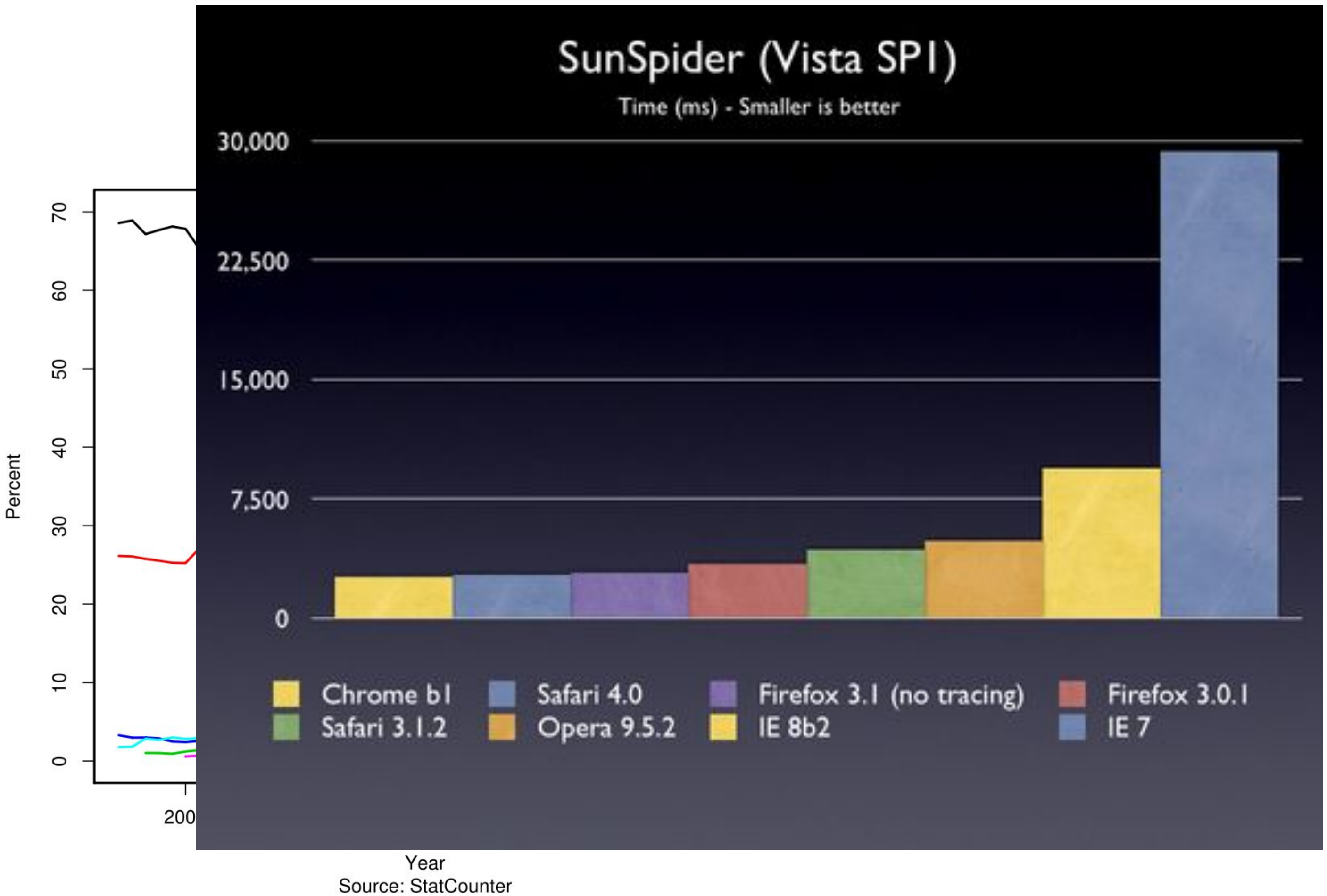
- New languages that are dynamic – challenging to compile
- Embedded applications – need specialized compilers (energy, space, cost are the constraints)





Why Study Compilers - 4

- What is the main factor influencing browser adoption ?



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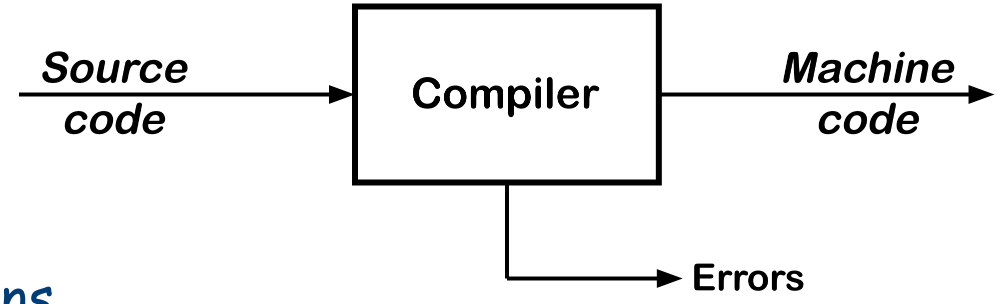
High-level View of a Compiler

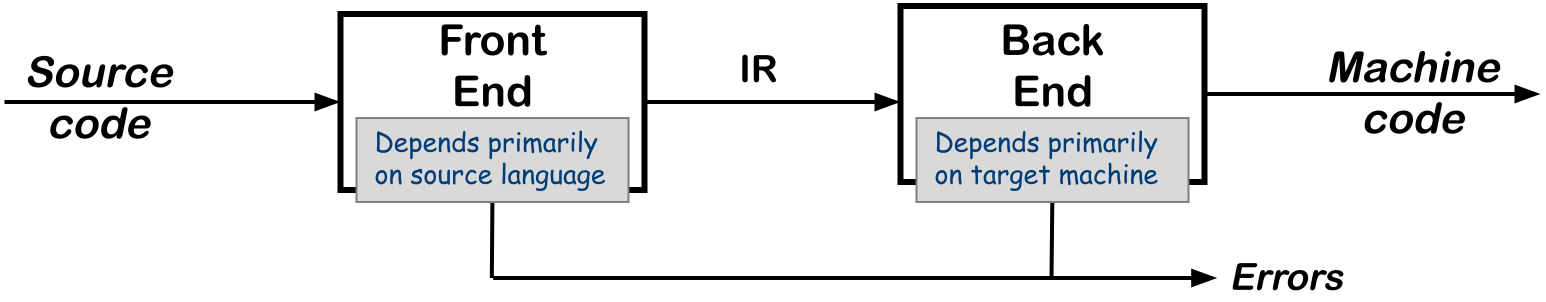


Implications

- 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



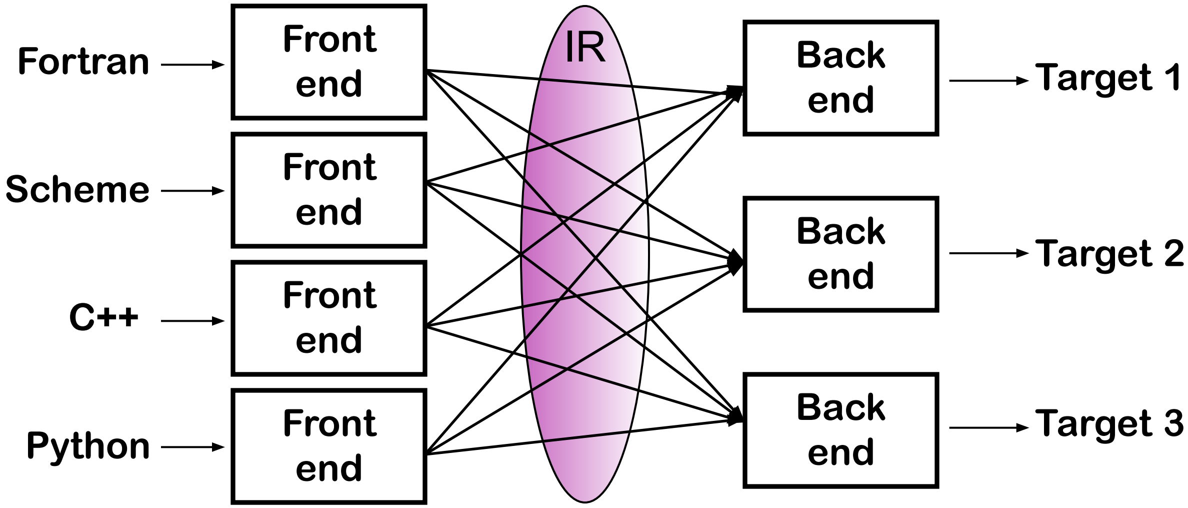
Implications

- 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)*

Classic principle from software engineering: Separation of concerns

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

A Common Fallacy



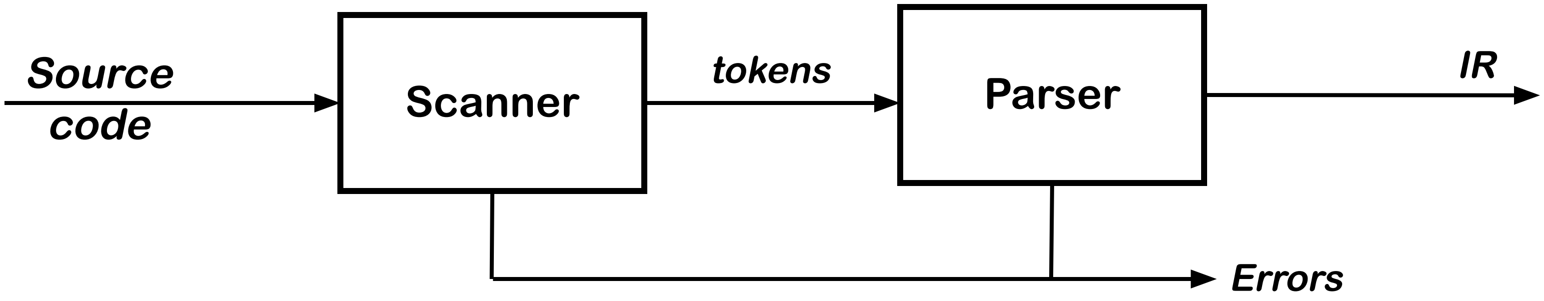
Can we build *n x m* compilers with *n+m* components?

- 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

Successful in systems with assembly level (or lower) IRs

e.g., gcc's rtl or llvm ir

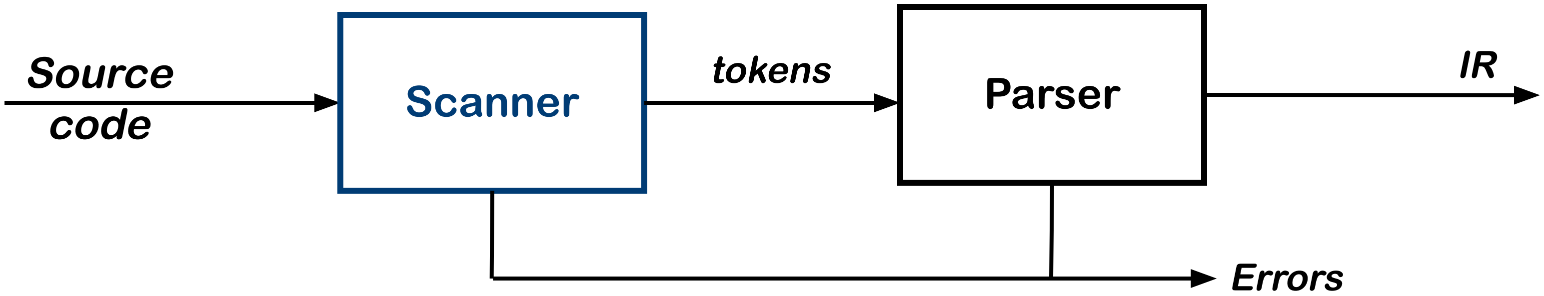
The Front End



Responsibilities

- Recognize legal (& illegal) programs
- Report errors in a useful way
- Produce IR & preliminary storage map
- Shape the code for the rest of the compiler
- 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

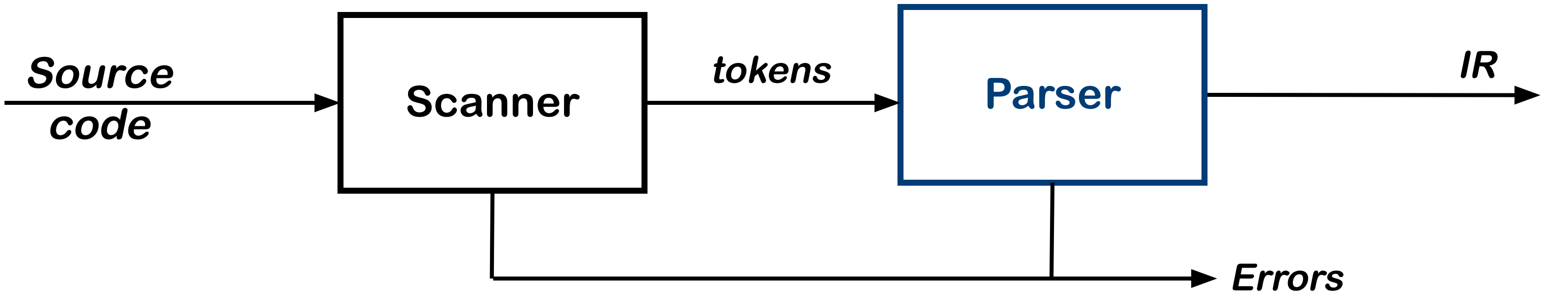
  x = x + y ; *becomes* <id,x> = <id,x> + <id,y> ;

  — *word ≅ lexeme, part of speech ≅ token type, pair ≅ a token*
- Typical tokens include *number*, *identifier*, +, –, new, *while*, *if*
- Speed is important

Textbooks advocate automatic scanner generation

Commercial practice appears to be hand-coded scanners

The Front End



Parser

- Recognizes context-free syntax & reports errors
- Guides context-sensitive ("semantic") analysis (*type checking*)
- Builds IR for source program (e.g., Abstract Syntax Tree)

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

$$\begin{aligned} \textit{SheepNoise} \rightarrow\ & \textit{SheepNoise}\ \underline{\text{baa}} \\ |\ & \underline{\text{baa}} \end{aligned}$$

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

(Example due to Dr. Scott K. Warren)

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 = { <u>number</u>, <u>id</u>, +, - }

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 *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

A derivation

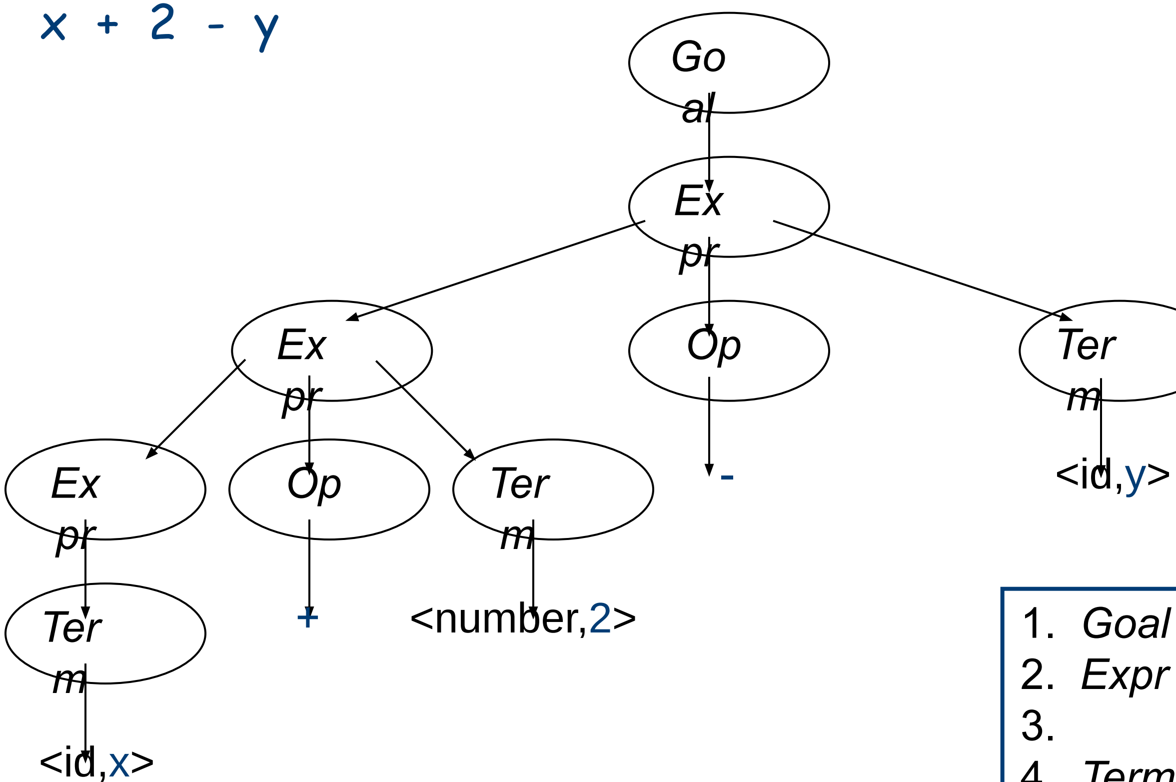
1. *Goal* → *Expr*
2. *Expr* → *Expr Op Term*
3. | *Term*
4. *Term* → number
5. | id
6. *Op* → +
7. | -

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* → number
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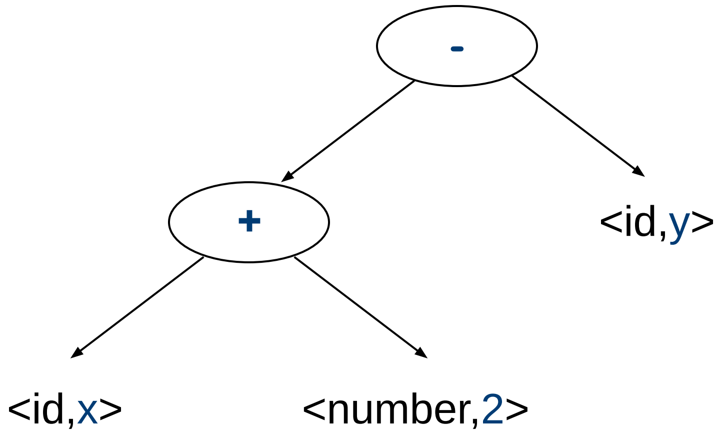
7. | -

The parse tree contains a lot of unneeded information

Abstract Syntax Tree (AST)



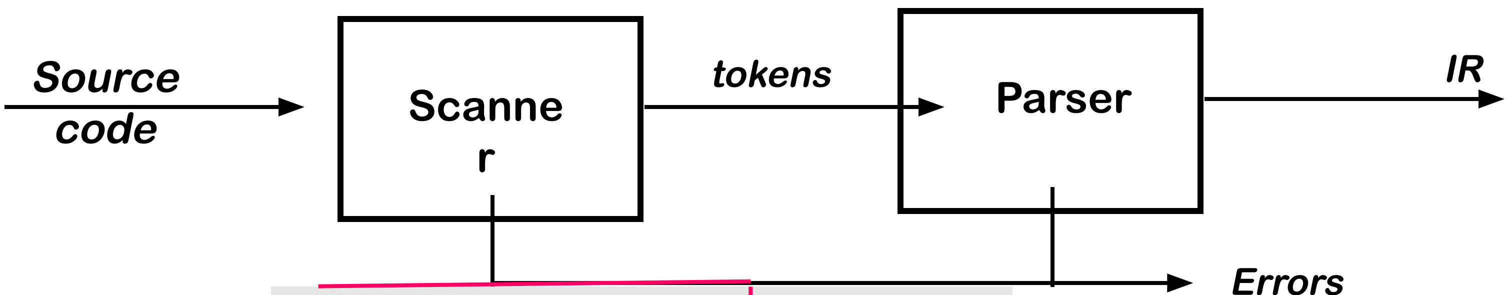
The AST summarizes grammatical structure, without including detail about the derivation

This is much more concise

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

Some people think that the AST is the "natural" IR.

The Front End



Is "a" distinct from b, c, & d ?

Code shape determines many properties of resulting program

a ← b x c + d
e ← f + b x c + d

becomes

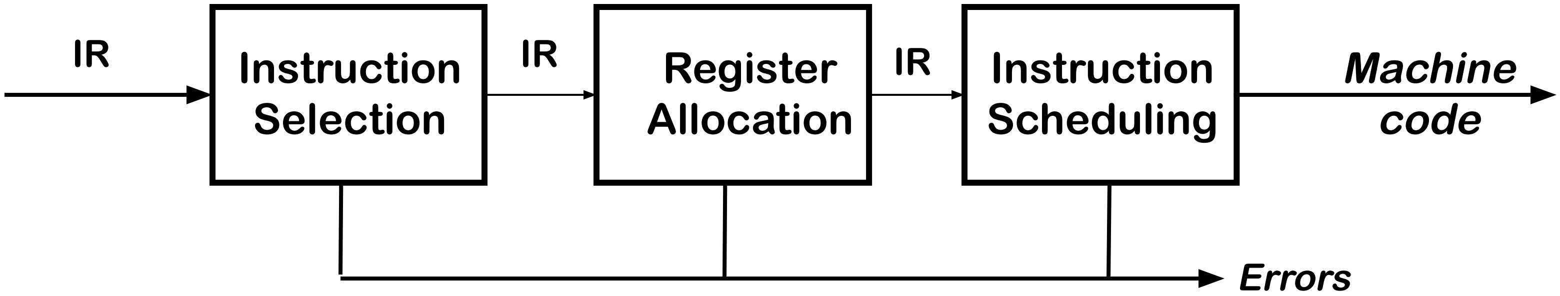
load @b ⇒ r_1
load @c ⇒ r_2
mult r_1,r_2 ⇒ r_3
load @d ⇒ r_4
add r_3,r_4 ⇒ r_5
store r_5 ⇒ @a
load @f ⇒ r_6
add r_5,r_6 ⇒ r_7
store r_7 ⇒ @e

computes b x c + d

reuses b x c + d

We would like to produce this code, but getting it right takes a fair amount of effort ….

The Back End

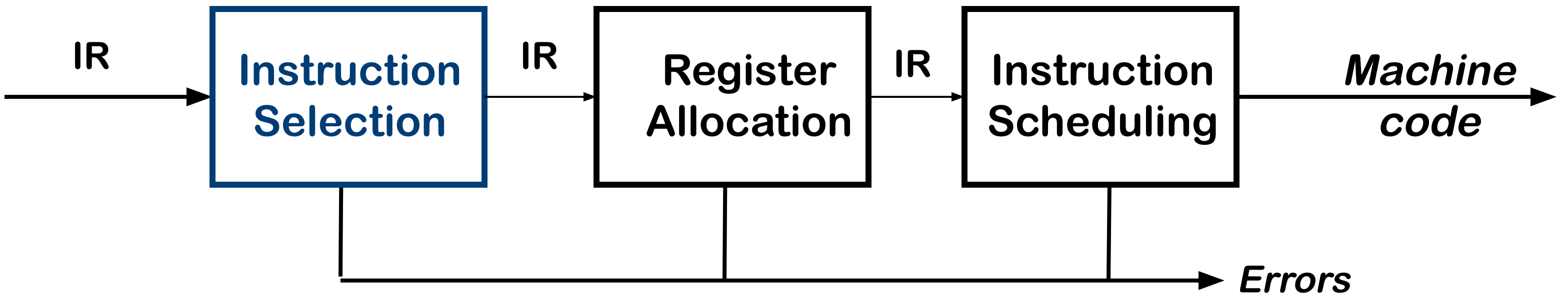


Responsibilities

- 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

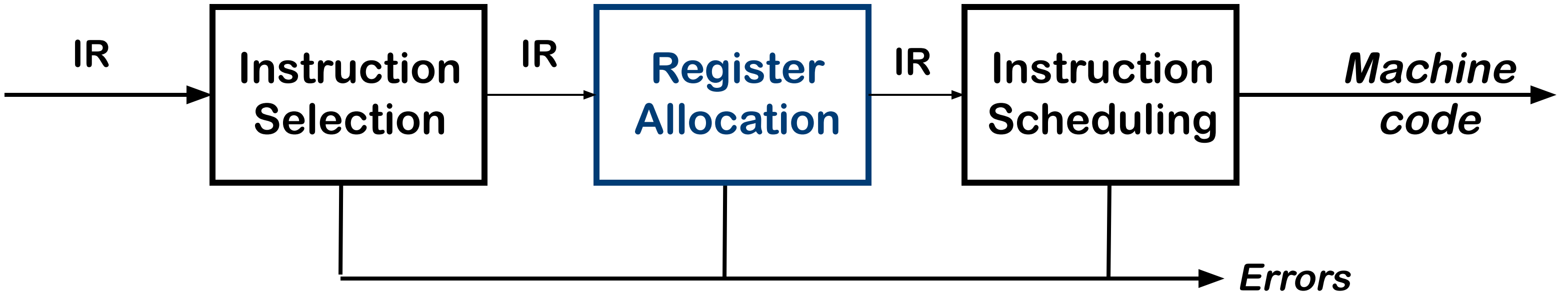
- Produce fast, compact code
- Take advantage of target features such as addressing modes
- Usually viewed as a pattern matching problem
  - *ad hoc* methods, pattern matching, dynamic programming
  - Form of the IR influences choice of technique

This was the problem of the future in 1978

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

Standard goal has become "locally optimal" code.

The Back End

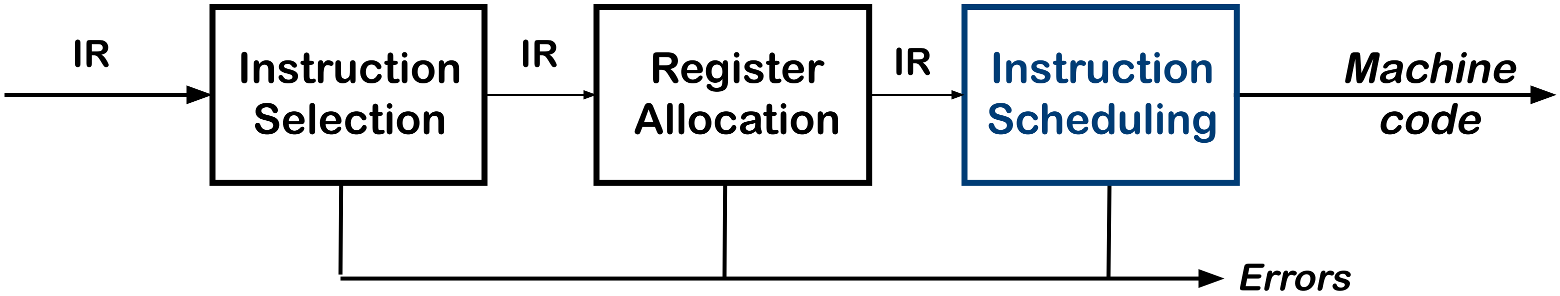


Register Allocation

- 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 in most settings

Compilers approximate solutions to NP-Complete problems

The Back End



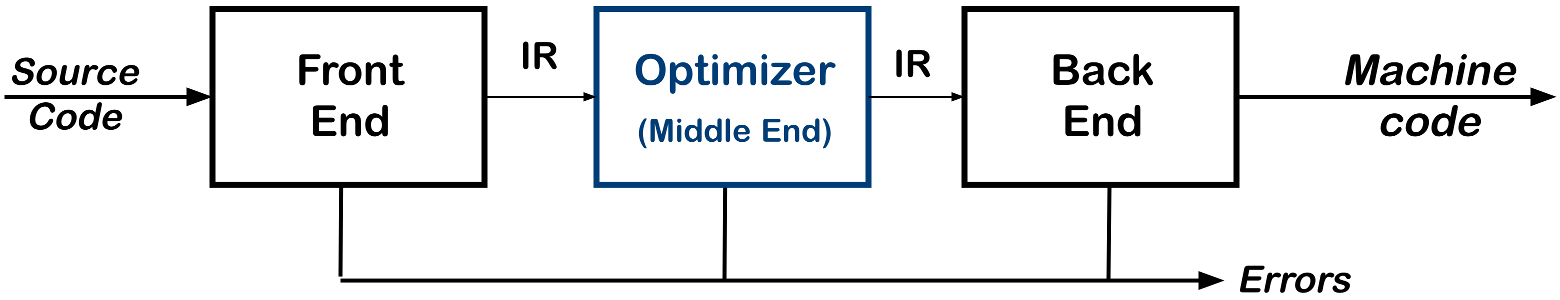
Instruction Scheduling

- 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-part Compiler

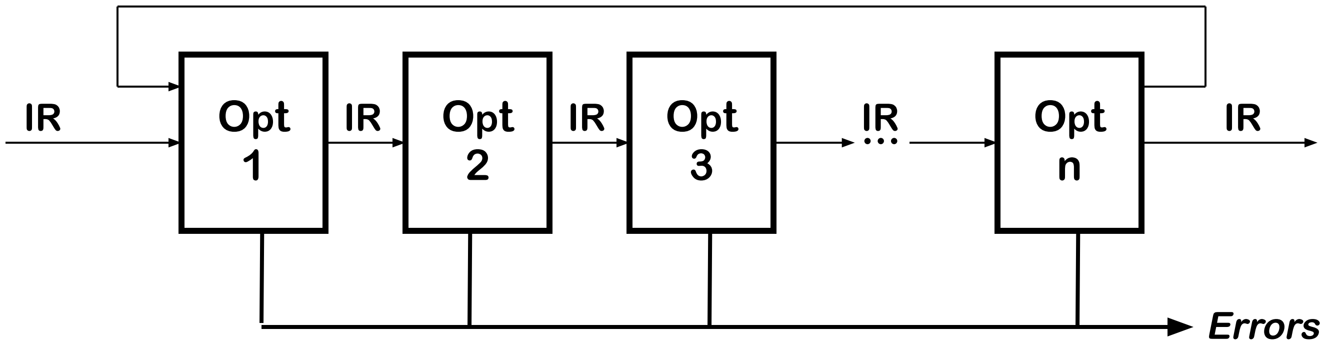


Code Improvement (or *Optimization*)

- 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

Subject of this course

The Optimizer (or Middle End)

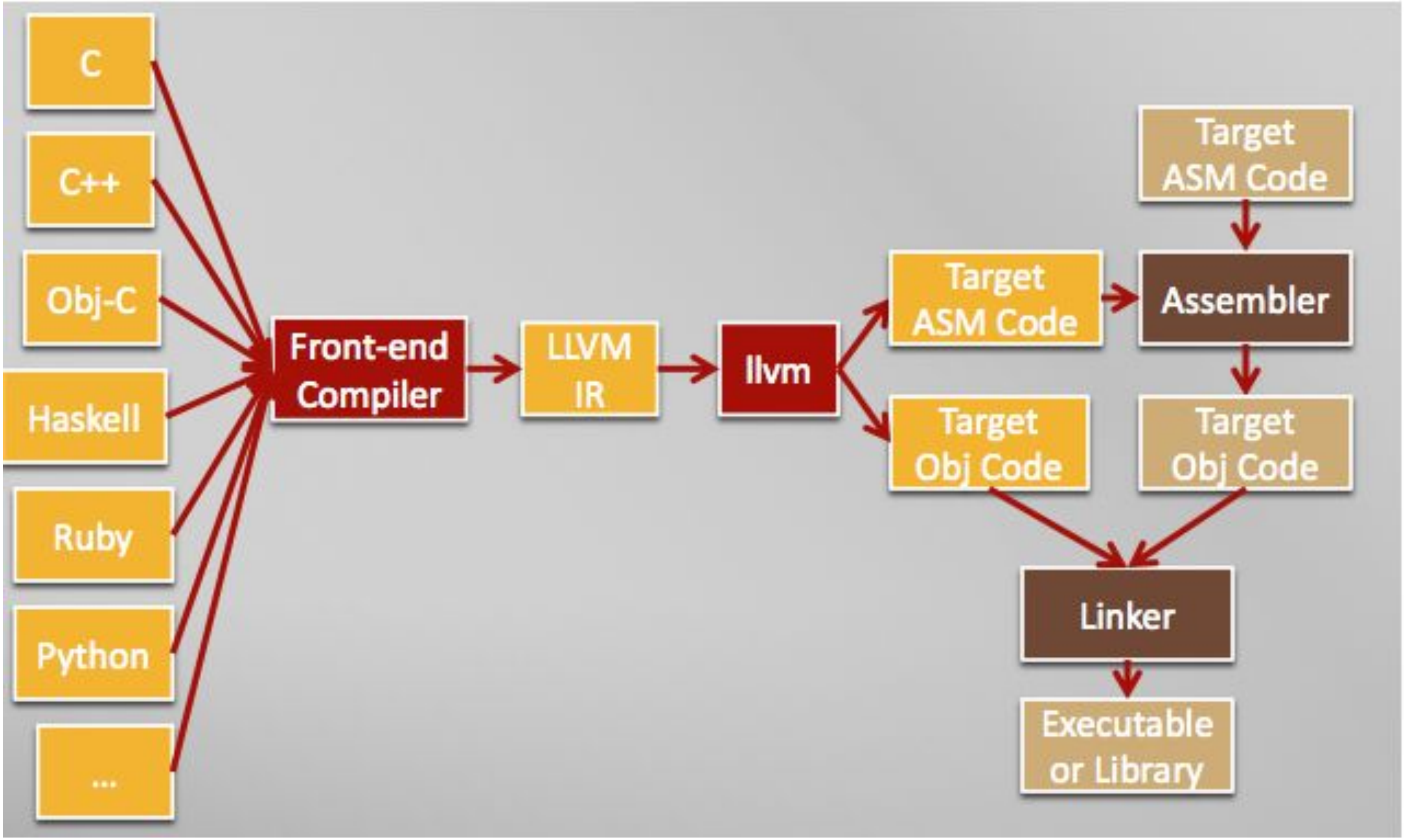


Modern optimizers are structured as a series of passes

Typical Transformations

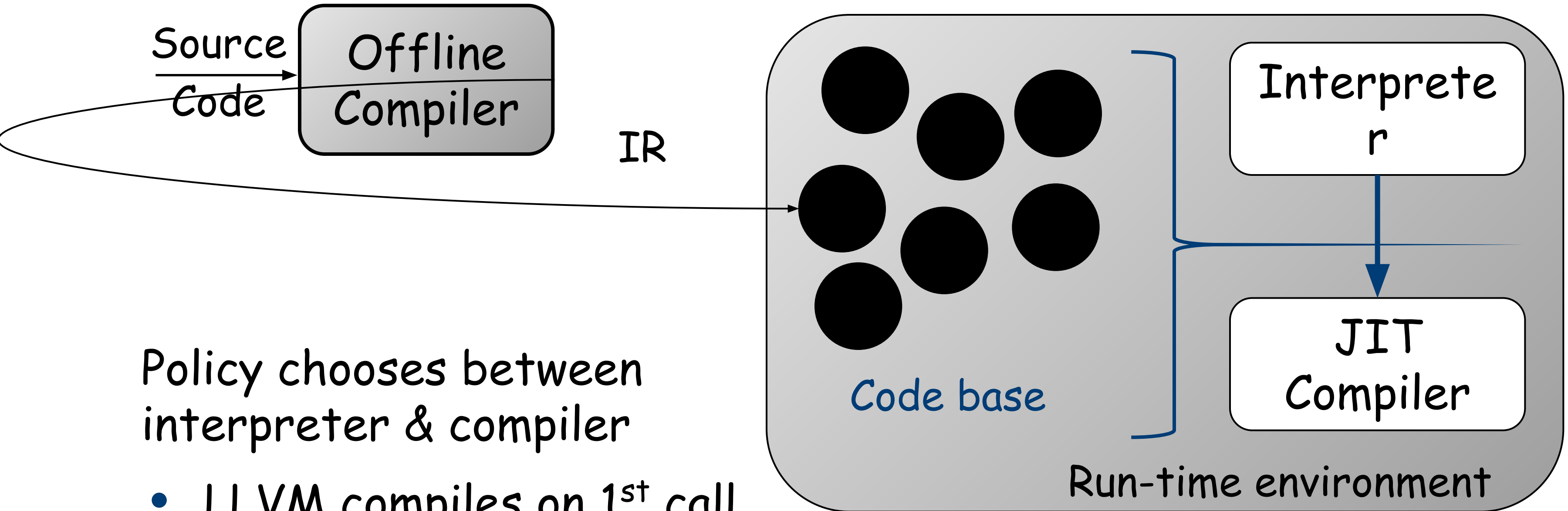
- Discover & propagate some constant value
- Move a computation to a less frequently executed place
- Specialize some computation based on context
- Discover a redundant computation & remove it
- Remove useless or unreachable code
- Encode an idiom in some particularly efficient form

LLVM Compiler Structure



Run-time Compilation

Systems such as HotSpot, Jalapeno, and Dynamo deploy compiler and optimization techniques *at run-time*

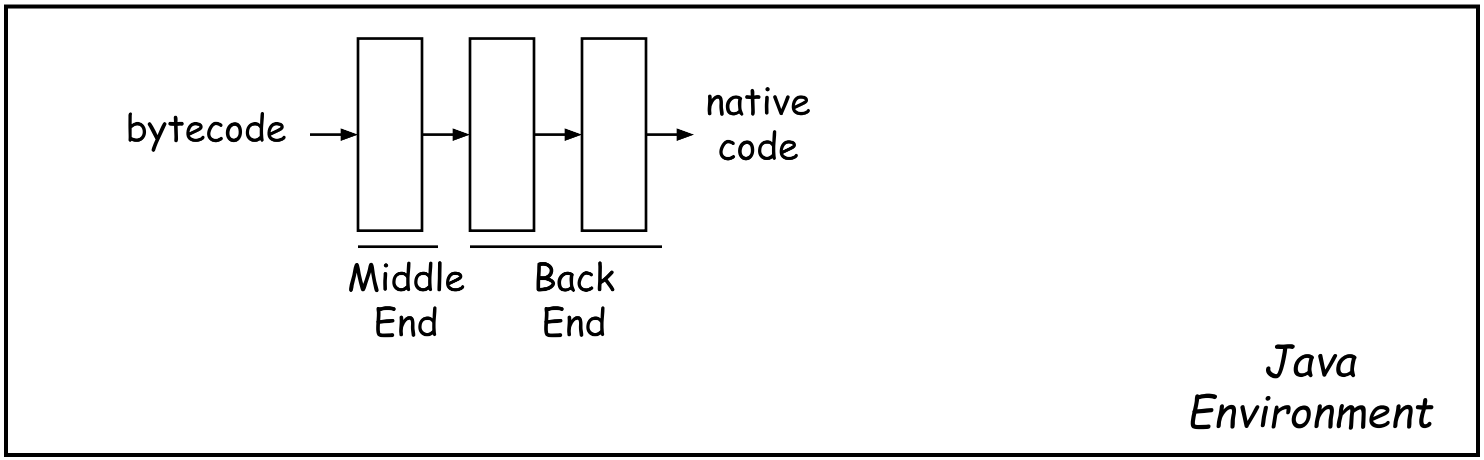


Policy chooses between interpreter & compiler

- LLVM compiles on 1st call
- Dynamo optimizes on 50th execution

JIT Compilers

Even a modern 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 a priori profitable

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

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- **Provide a brief summary of the history of compilers and the state of the art today**

First FORTRAN compiler

- John Backus on the Fortran Compiler (around 1958)

- "It is our belief that if FORTRAN, during its first months, were to translate any reasonable scientific program into an object program only half as fast as its hand-coded counterpart, then acceptance of our system would be in serious danger. ...
- "To this day I believe that our emphasis on object program efficiency rather than on language design was basically correct. I believe that had we failed to produce efficient programs, the widespread use of languages like FORTRAN would have been seriously delayed."

- – John Backus, Fortran I, II and III, *Annals of the History of Computing*, vol. 1, no. 1, July 1979.

A Sense of History

1955-1959	*Commercial compilers generated good code*
Fortran	Separation of concerns (Backus, 1956)
Cobol	Control-flow graph, register allocation (Haibt, 1957)
1960–1964	*Academics try to catch up with industrial trade secrets*
Algol 60	Early algorithms for "code generation" (1960, 1961)
	Relating theory to practice (Lavrov, 1962)
	Alpha project at Novosibirsk (Ershov, 1963 & 1965)
1965-1969	*Technology begins to spread*
PL/I	Fortran H (Medlock & Lowry, 1967)
Algol 68	Value numbering (Balke, 1967 ?)
Simula 67	Literature begins to emerge (Allen, 1969)

A Sense of History

1970-1974	*The literature explodes and optimization grows up*
SETL	Cocke & Schwartz, Allen-Cocke Catalog, 1971
Smalltalk	Theory of analysis (Kildall, 1971, Allen & Cocke, 1972)
Lisp	Interprocedural analysis (Spillman,1972)
APL	Strength reduction, dead code elimination, Live (SETL)
	Expression tree algorithms (Sethi, Aho & Ullman)
1975-1979	*Global optimization comes of age*
Pascal	Full literature of data-flow analysis
CLU	Strength reduction (Cocke & Kennedy, 1977)
Alphard	Partial redundancy elimination (Morel & Renvoise, 1979)
Com. Lisp	Inline substitution studies (Scheiffler, 1977, Ball, 1979)
	Tail recursion elimination (Steele, 1978)
	Data dependence analysis (Bannerjee, 1979)

A Sense of History

1980-1984	*Programming environments and new architectures*
Smalltalk80	Incremental analysis (Reps, 1982; Ryder, Zadeck, 1983)
ADA	Incremental compilation (Schwartz *et al.*, 1984)
Scheme	Interprocedural analysis (Myers, 1981; Cooper, 1984)
	RISC compilers (PL.8, 1980; MIPS, 1983)
	Graph coloring allocation (Chaitin, 1981; Chow, 1983)
	Vectorization (Wolfe, 1982; R. Allen, 1983)

1985–1989	*Resurgence of interest in classical optimization*
C++	Constant propagation (Wegman & Zadeck,Torczon,1985)
ML	Code motion of control structures (Cytron *et al.*, 1986)
Modula-3	Value numbering (Alpern *et al.*, Rosen *et al.*, 1988)
	Software pipelining (Lam, Aiken & Nicolau, 1988)
	Pointer analysis (Ruggeri, 1988)
	SSA-form (Cytron *et al.*, 1989)

A Sense of History

1990-1994	*Architects (and memory speed) drive the process*
Fortran 90	Hierarchical allocation (Koblenz & Callahan,1991)
	Scalar replacement (Carr 1991)
	Cache blocking (Wolf, 1991)
	Prefetch placement (Mowry, 1992)
	Commercial interprocedural compilers (Convex, 1992)
1995–1999	*The internet & SSA both come of age*
Java	JIT compilers (Everyone, from 1996 to present)
Perl (?)	Code compression (Franz, 1995; Frasier et al., 1997; ...)
	SSA-based formulations of old methods (lots of papers)
	Compile to VM (Java, 1995; Bernstein, 1998; …)
	Memory layout optimizations (Smith, 19??; others …)
	Widespread use of analysis (pointers, omega test, …)

*

The state of compilers today: My subjective view

- 2000 to 2005: Expansion beyond classical optimization
  - Dawson Engler's work on finding bugs in the Linux Kernel (2001)
  - Work by Manuvir Das on protocol violation errors (2002)
  - SLAM at MSR for model checking of C code (2001)
  - MOPS by David Wagner for security property checking (2001)
  - Findbugs by William Pugh for bug pattern detection (2004)

- 2005 to 2010: Program synthesis, energy/power, Web 2.0
  - Program sketching by Solar Lezama et al (2005, 2006)
  - Program synthesis by Gulwani (2007-2014)
  - Failure oblivious computing by Rinard (2005- 2014)
  - Fault-tolerance by Berger, Pattabiraman, Zorn (2005-2014)
  - Energy savings through relaxed correctness – Sankaralingam, Chillimbi, Pattabiraman, Grossman, Ceze (2009 to 2014)
  - Fast compilation of JavaScript programs (2010 onwards)
  - Analysis of programs for continuity (Gulwani and Chaudhri)

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