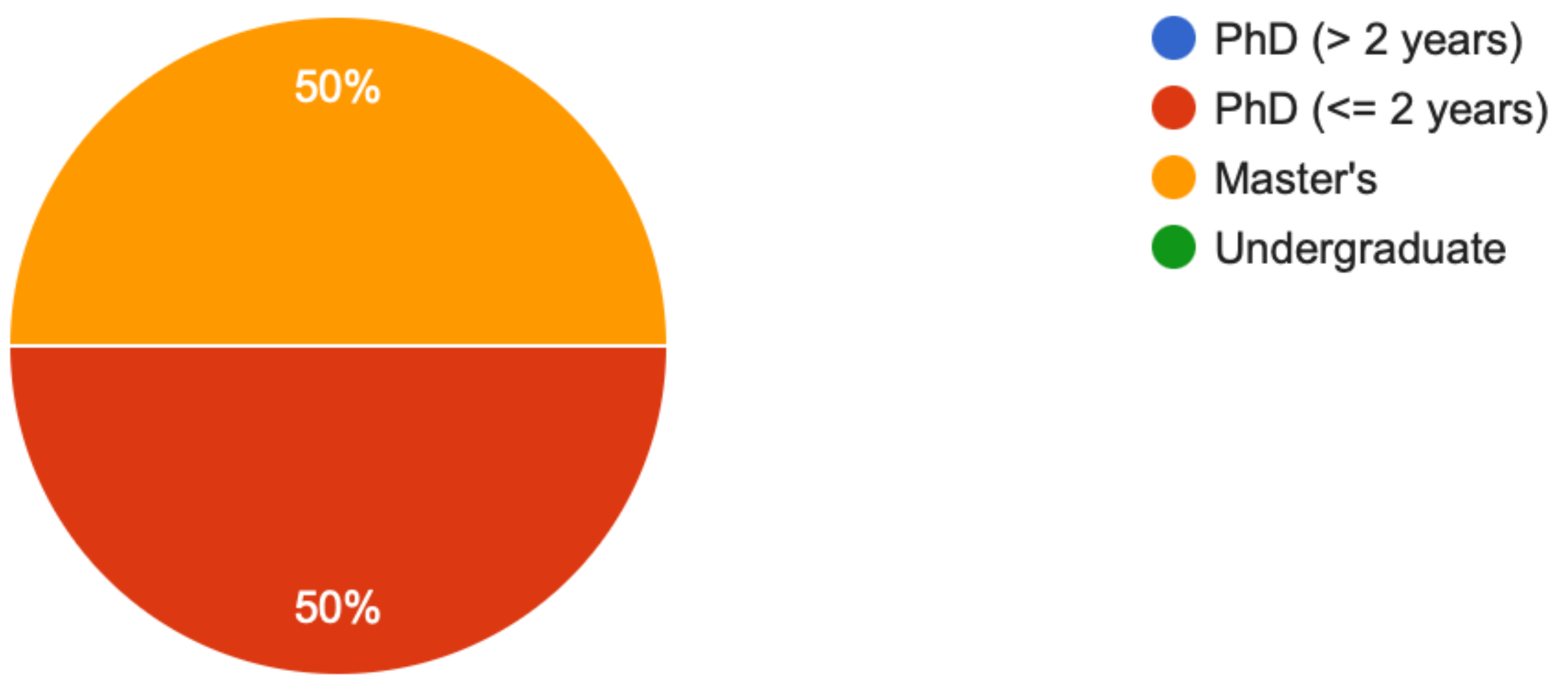
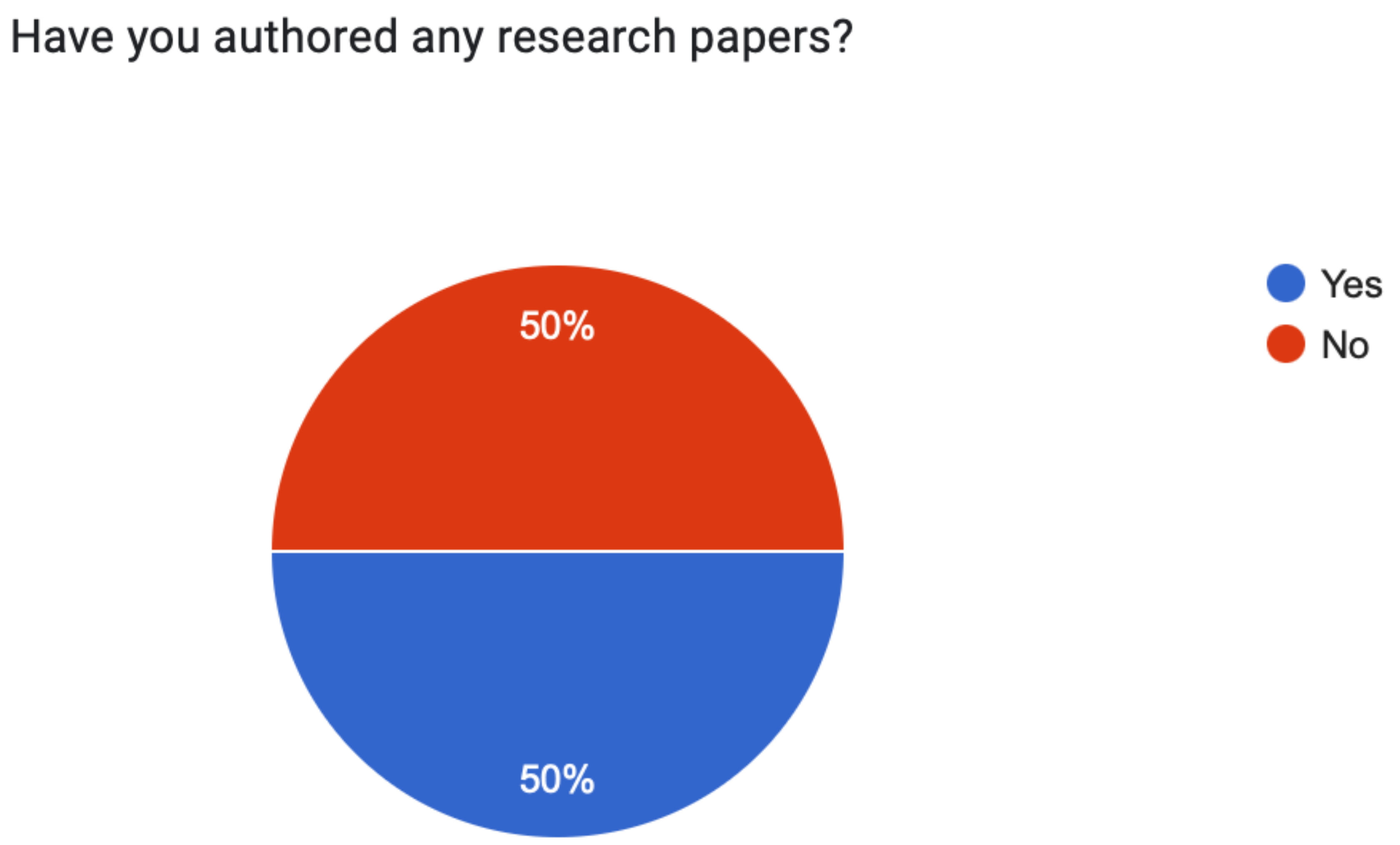
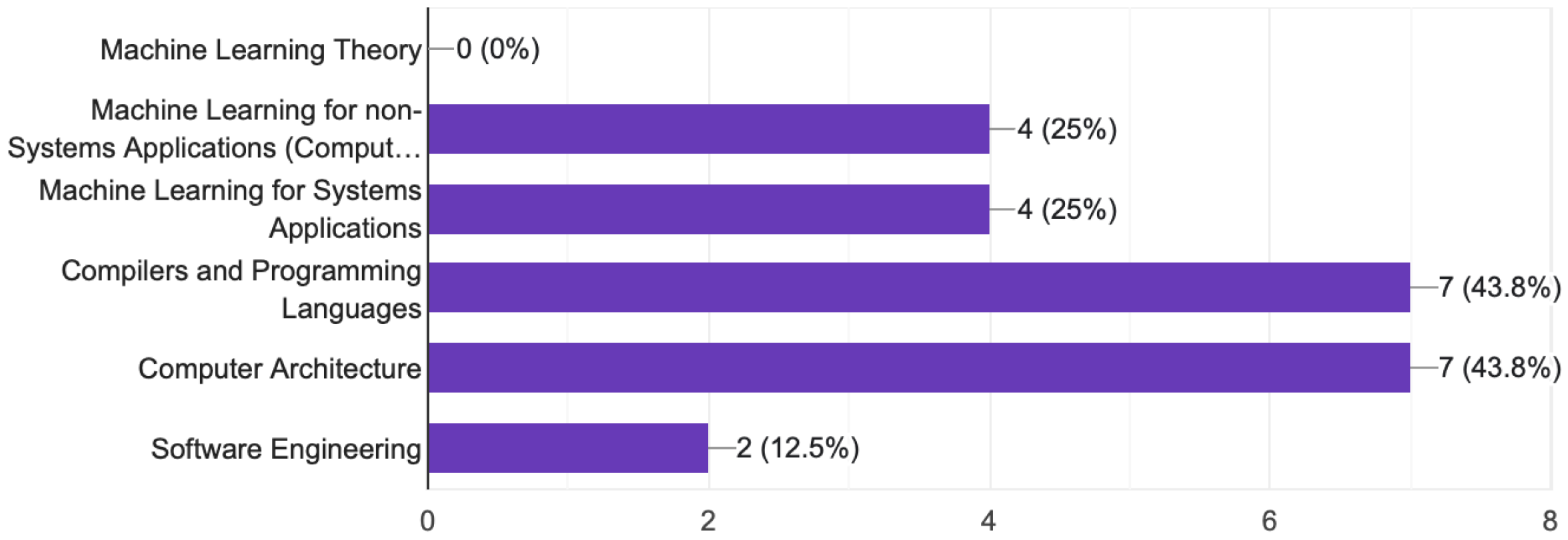
CS 598CM: ML for Compilers and Architecture

Instructor: Charith Mendis

Class Statistics Survey Results







Brief Announcements

- **Pre-requisites:** CS 426, CS 433, CS 421
  - The instructor lectures should be considered as crash courses
  - Willing to learn as you go
- **Reading List:** Up on the website
- **Paper Selections:** Due on August 31st; link on the website.

Lecture 2: Compilers

Crash-course + Optimizations

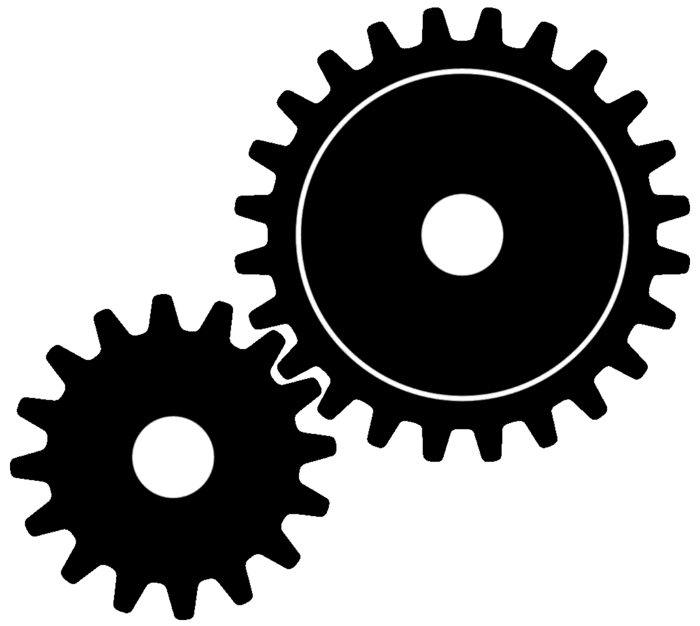
Compilers translate high-level languages to low-level machine code

Program

```
for (i = 0; i < grid_points[0]; i++)
  for (j = 0; j < grid_points[1]; j++)
    for (k = 0; k < grid_points[2]; k++)
      for (m = 0; m < 5; m++)
         add = u[i][j][k][m] − u_exact[m];
         rms[m] = rms[m] + add*add;
```

High-level programming language

Compiler



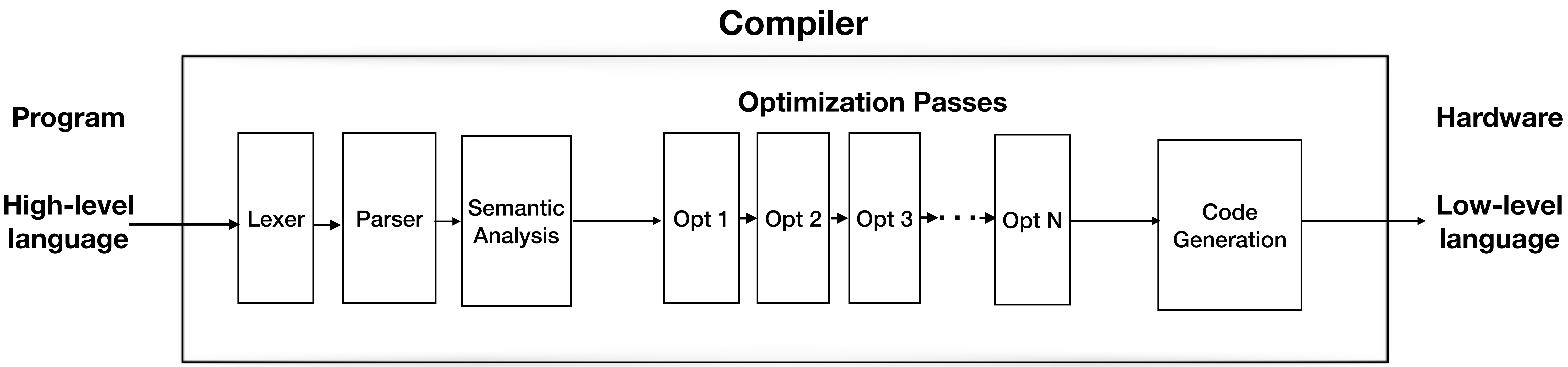
Hardware

```
......
addq    %rcx, %rax
movq    %rax, %rcx
salq    $6, %rcx
addq    %rcx, %rax
imulq   $21125, %rdi, %rcx
addq    %rax, %rcx
movq    %rdx, %rax
salq    $2, %rax
addq    %rsi, %rax
......
```

Low-level assembly language

Finding a semantic preserving (correct) translation that generates fast (optimized) code

Stages of a Compiler



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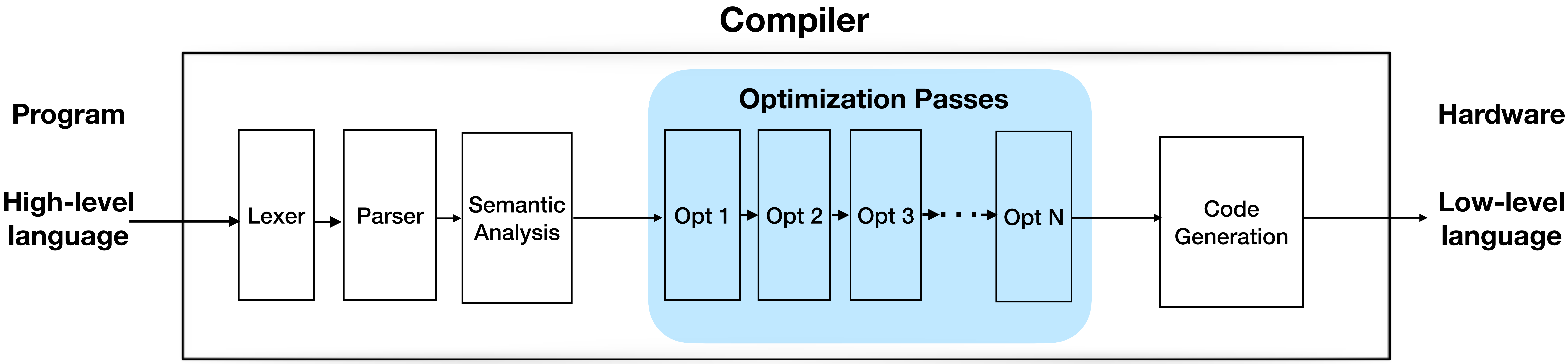
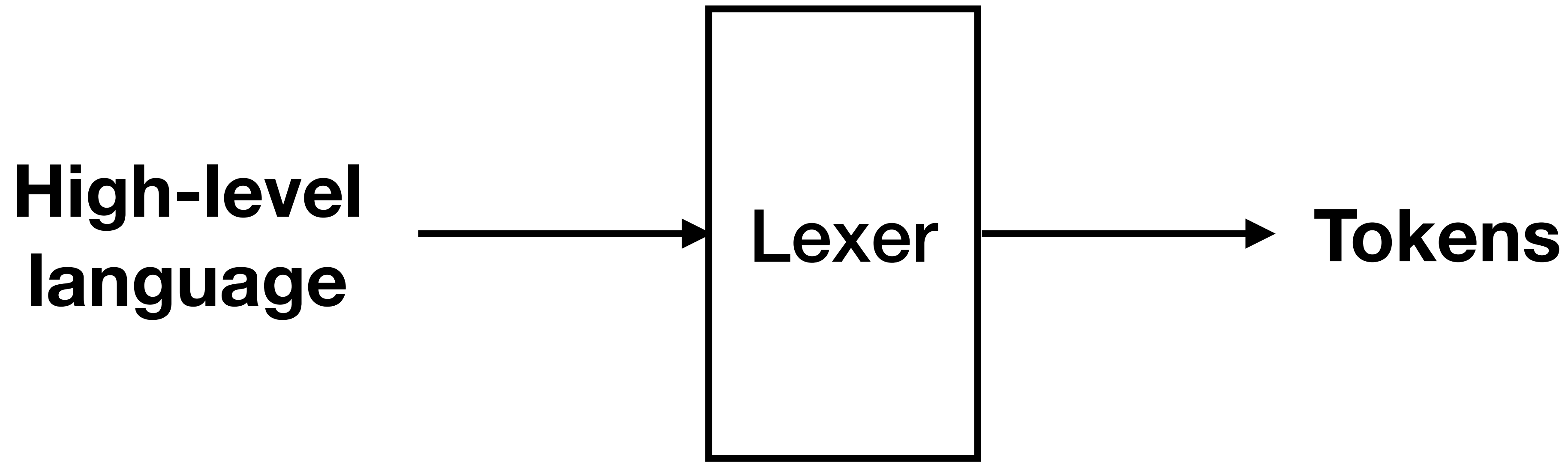


Lexer



List or stream of strings with syntactic meaning

```
for (int i= 0; i <100; i++){
   A[i] = A[i+1] + 1;
}
```

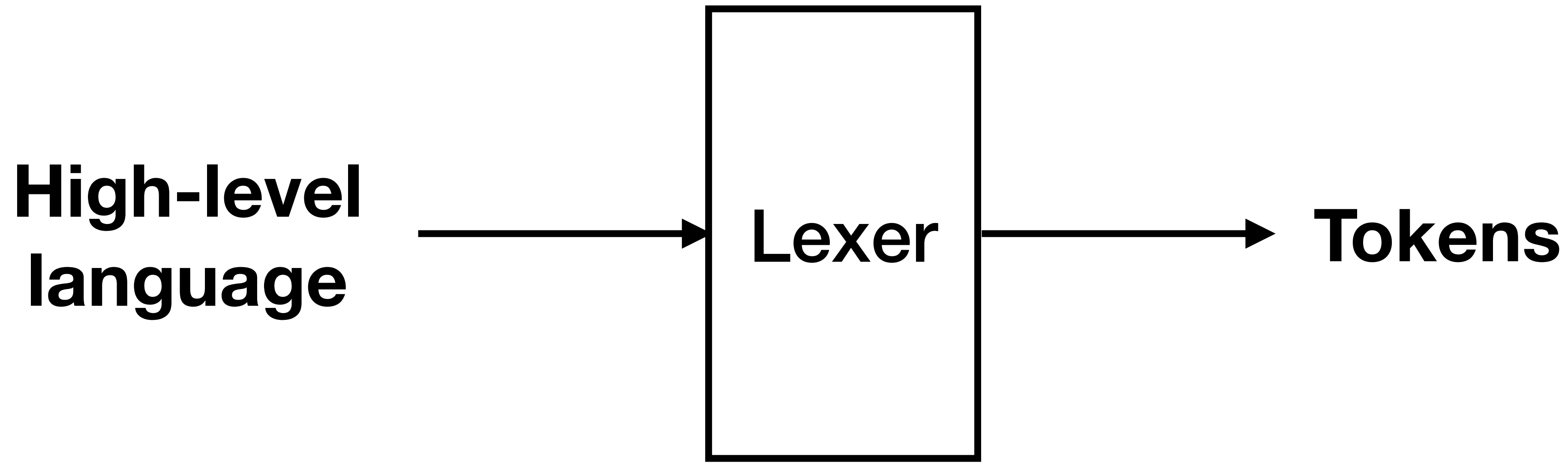
<for> <(> <int> ... <A> <[> <i> <]> ...

Keywords

Separators

Identifiers

Lexer



What errors does lexer catch?
Usually lexer produces tokens from regular languages

```
for (int i= 0; i <100; i++){
   A[i] = A[i+1] + 1;
}
```

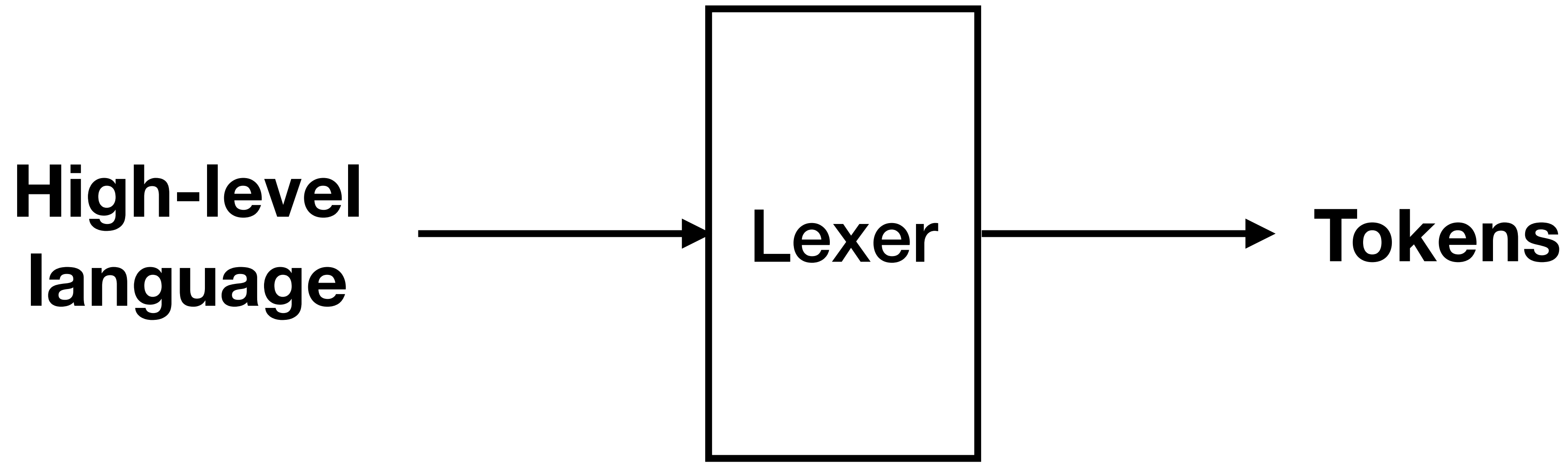
✓

```
for (int i= 0; i <100; i++){
   A[i = A[j+1] + 1;
}
```

```
for (int i= 0; i <100; i++){
   A[i] = A[j+1] + 1;
}
```

```
for (int i= 0; i <100n; i++){
   A[i = A[j+1] + 1;
}
```

Lexer



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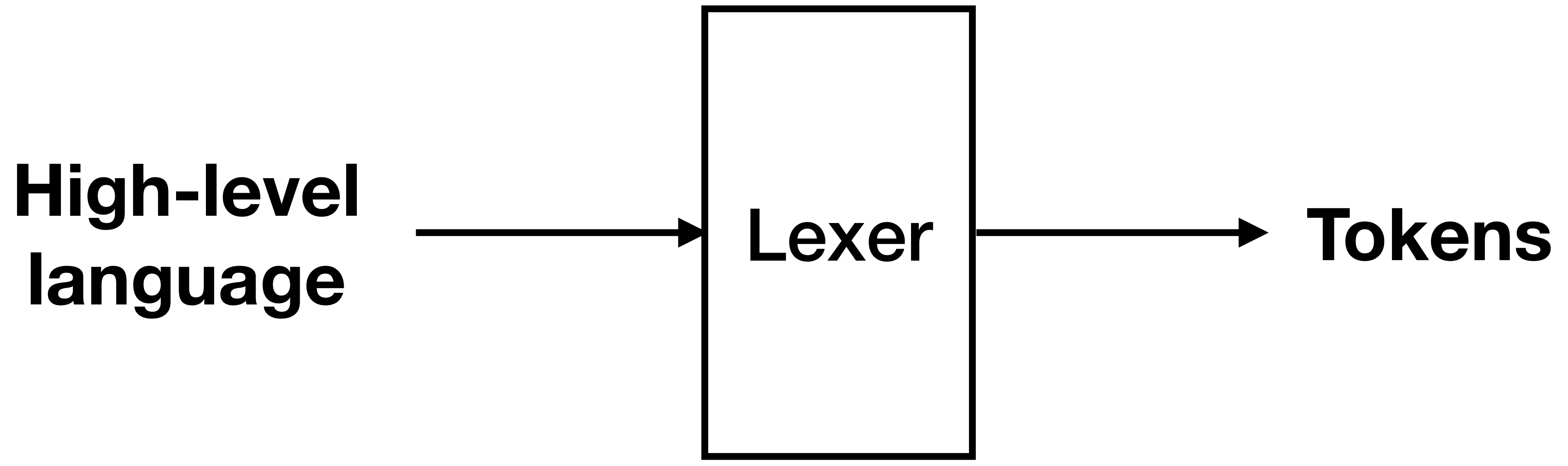
Lexer



What errors does lexer catch?
Usually lexer produces tokens from regular languages

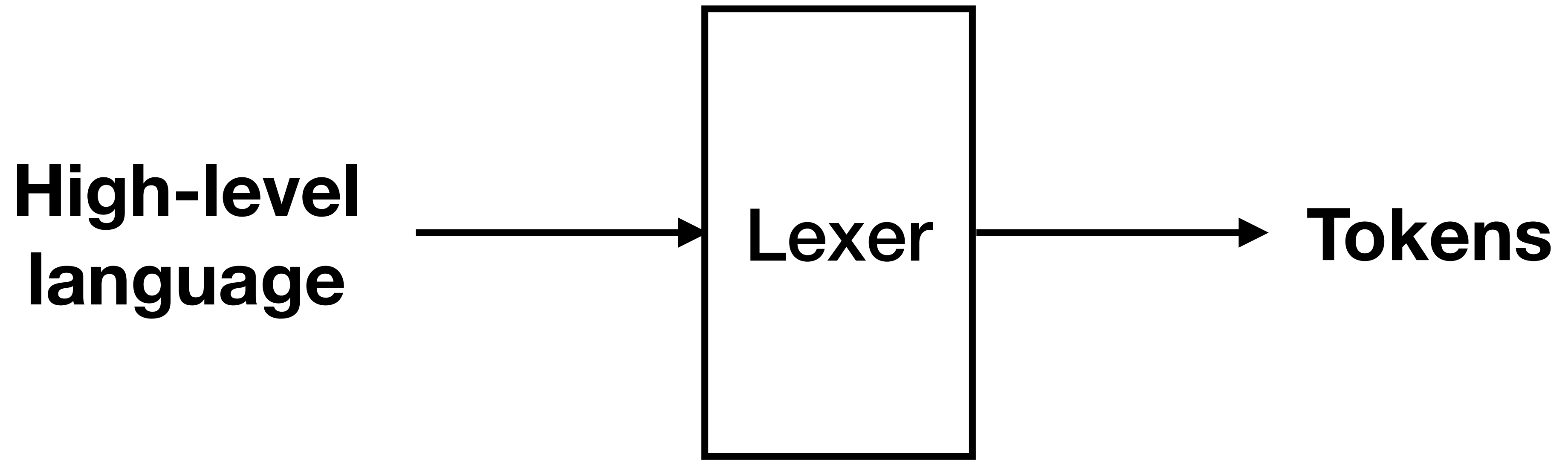
```
for (int i= 0; i <100; i++){
   A[i] = A[i+1] + 1;
}
```

```
for (int i= 0; i <100; i++){
   A[i?= A[j+1] + 1;
}
```

```
for (int i= 0; i <100; i++){
   A[i] = A[j+1] + 1;
}
```

```
for (int i= 0; i <100n; i++){
   A[i = A[j+1] + 1;
}
```

Lexer



What errors does lexer catch?
Usually lexer produces tokens from regular languages

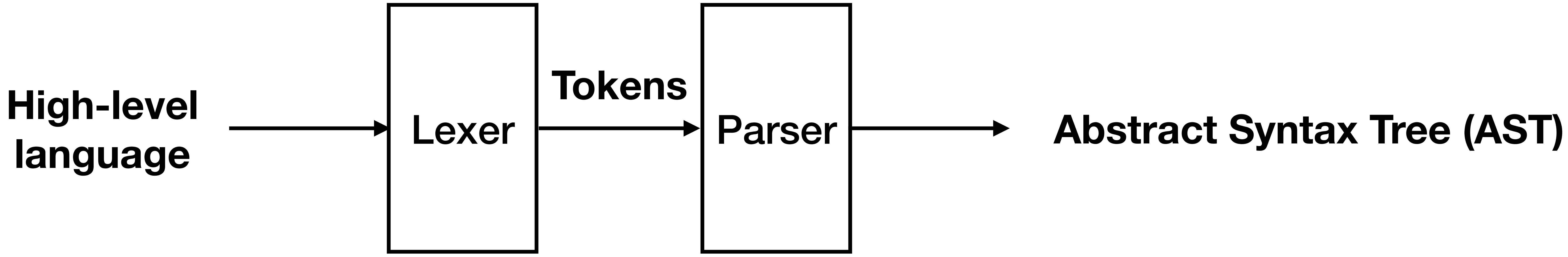
```
for (int i= 0; i <100; i++){
   A[i] = A[i+1] + 1;
}
```
✓

```
for (int i= 0; i <100; i++){
   A[i?= A[j+1] + 1;
}
```
✓

```
for (int i= 0; i <100; i++){
   A[i] = A[j+1] + 1;
}
```
✓

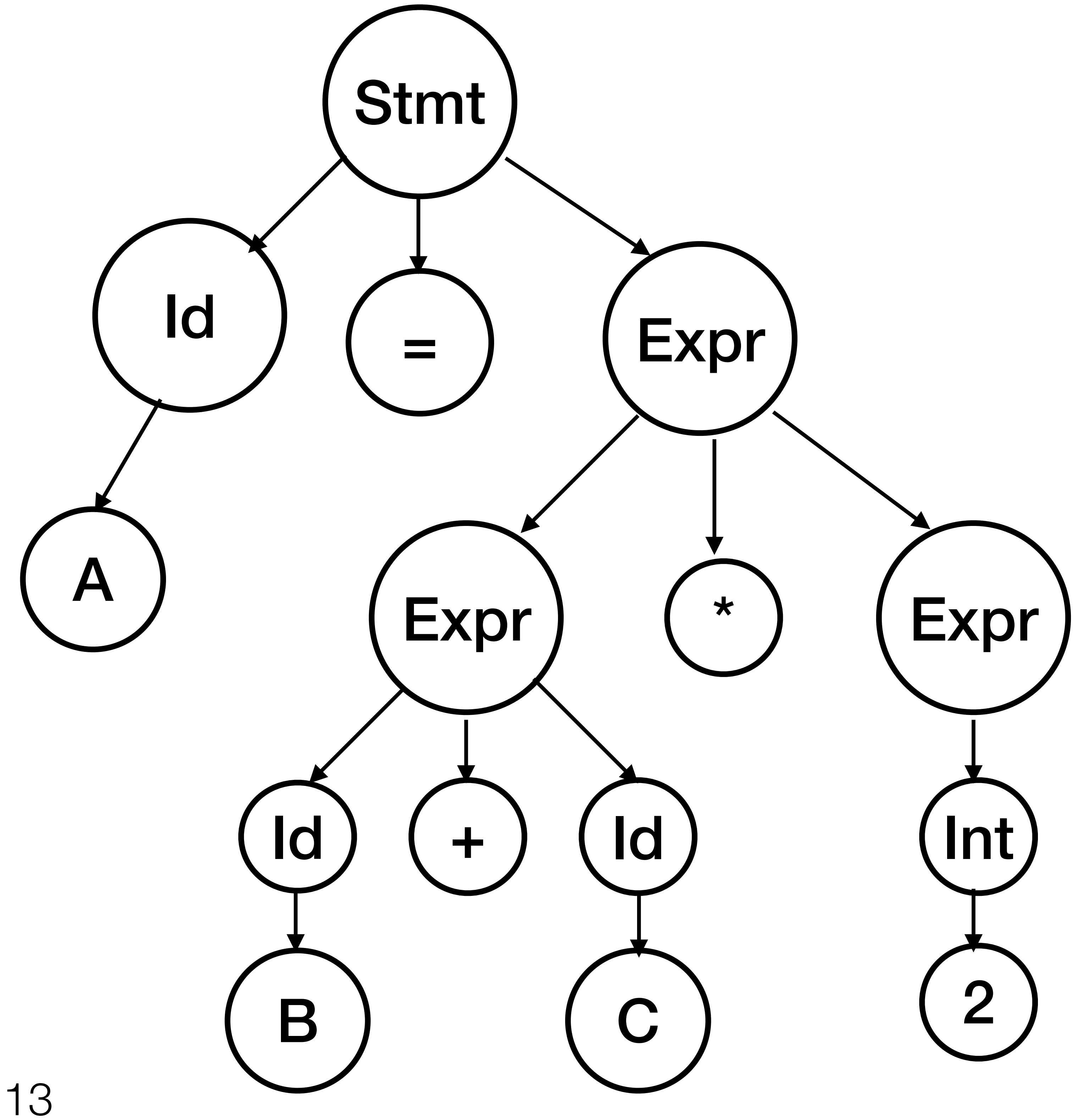
```
for (int i= 0; i <100n; i++){
   A[i = A[j+1] + 1;
}
```
✗

Parser



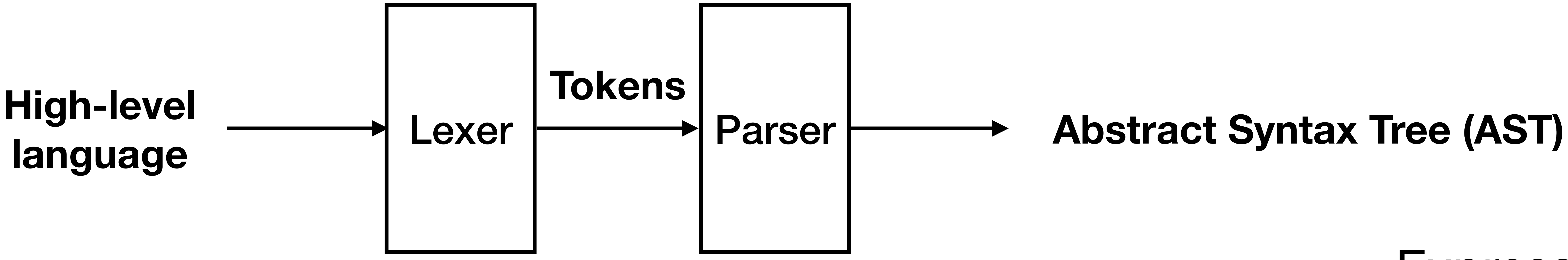
High-level language
Lexer
Tokens
Parser
Abstract Syntax Tree (AST)

A = (B + C) * 2;



Stmt
Id
=
Expr
A
Expr
*
Expr
Id
+
Id
Int
B
C
2

Parser



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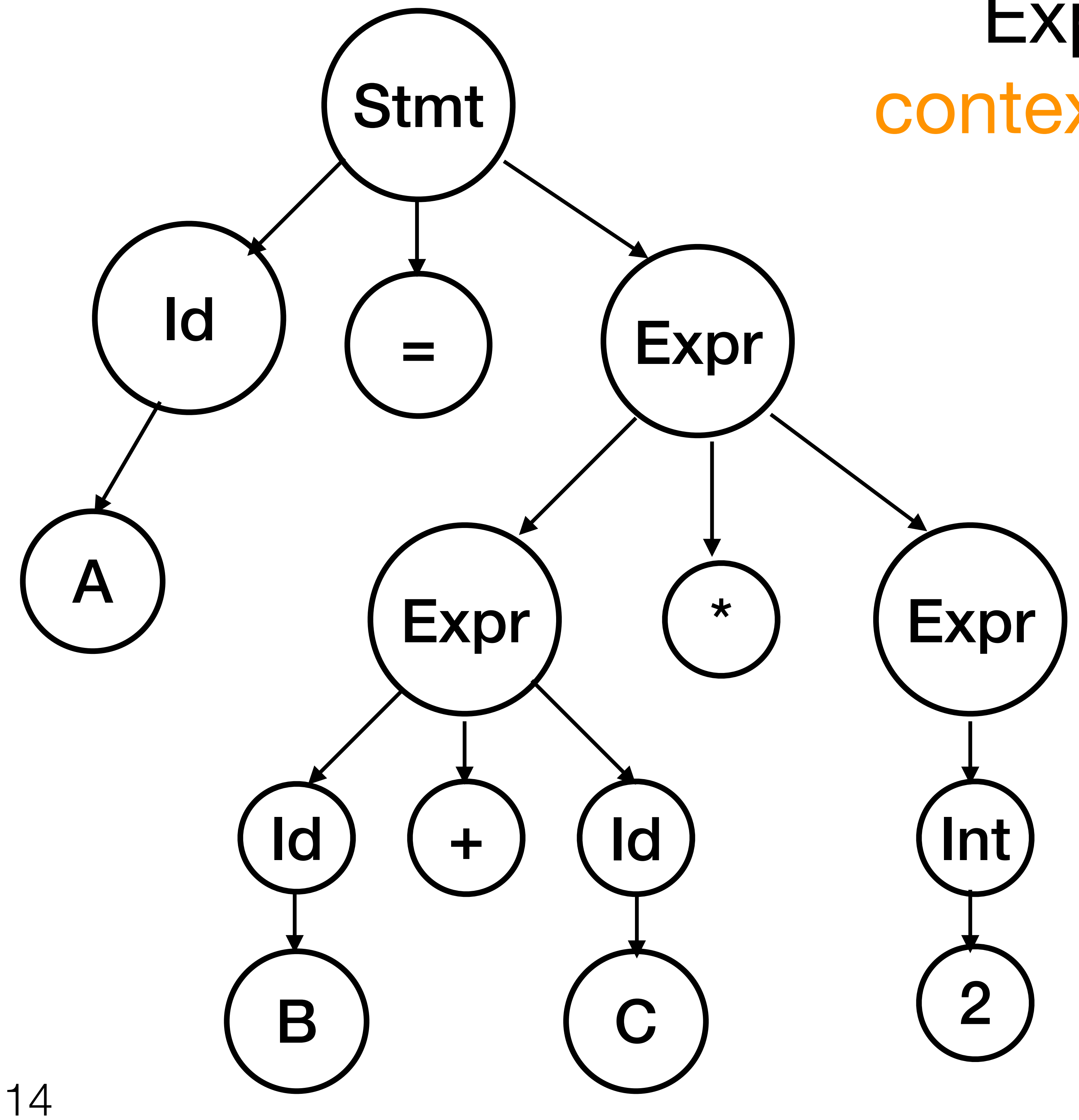
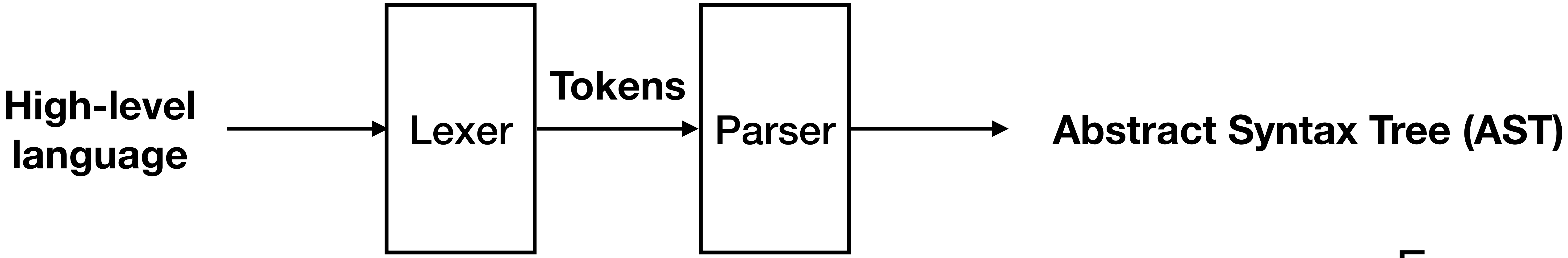


Expressed as a context-free grammar

Parser



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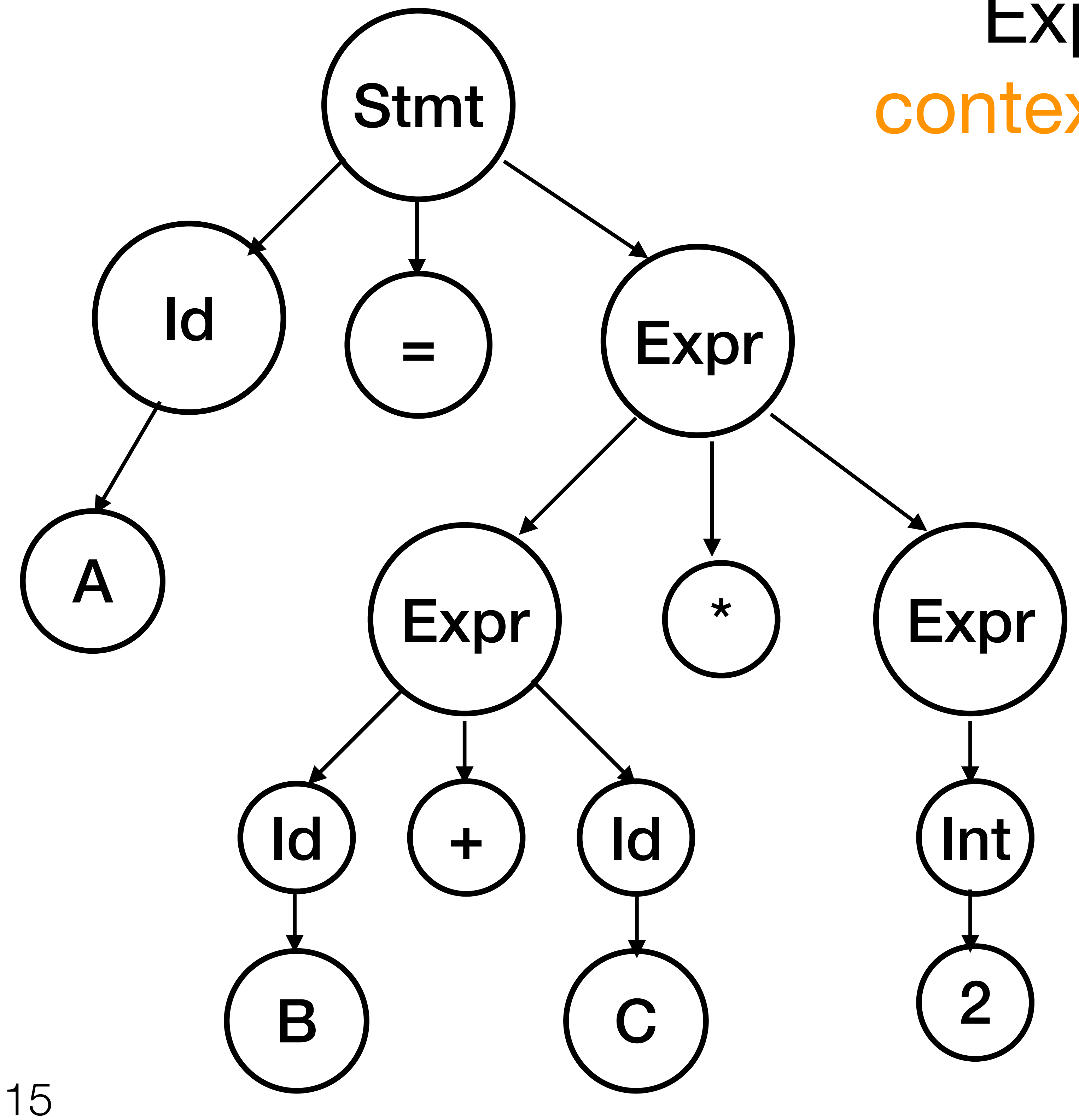
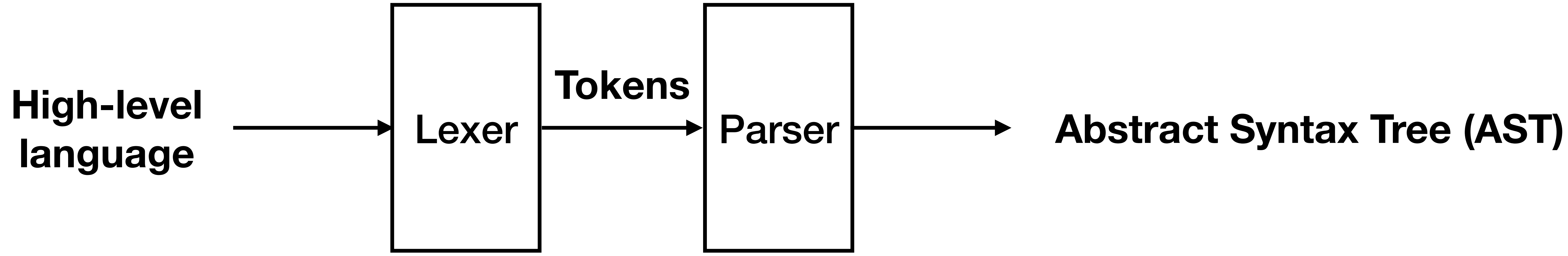


A = (B + C) * 2; ✓

A = (B + C * 2; ✗

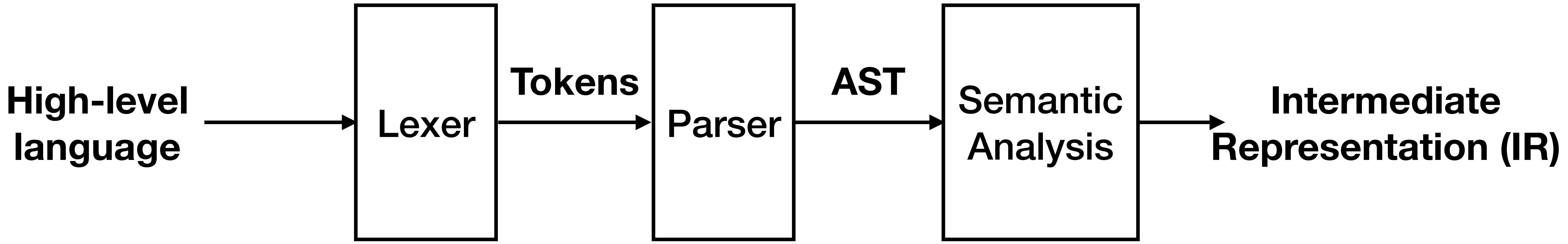
A = (B + C * 2 ✗

Parser



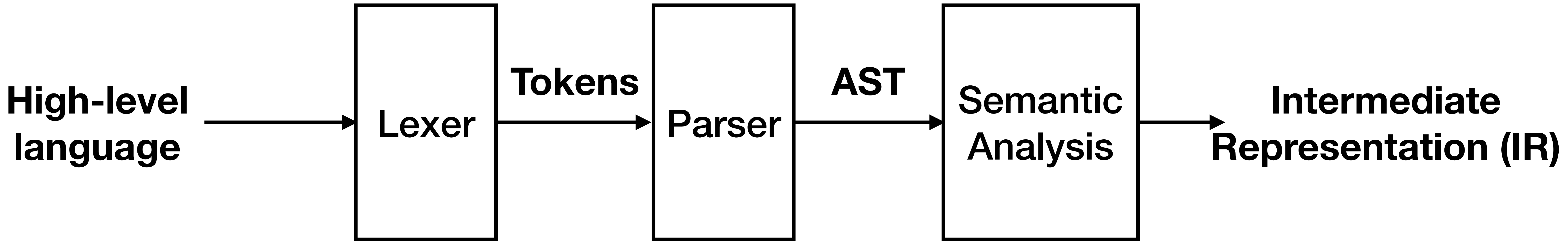
- Does not check if variables are defined
- Does not have scopes; variable bindings not defined
- Control flow or data flow information is not explicit

Semantic Analysis



- Clear variable bindings
- Control flow or data flow information embedded and queryable
- Focuses on the meaning of code (what computation does it perform?)
- Many IRs exist even in a single compiler

Semantic Analysis



- Clear variable bindings
- Control flow or data flow information embedded and queryable
- Focuses on the meaning of code (what computation does it perform?)
- Many IRs exist even in a single compiler

Semantics - we can now optimize!

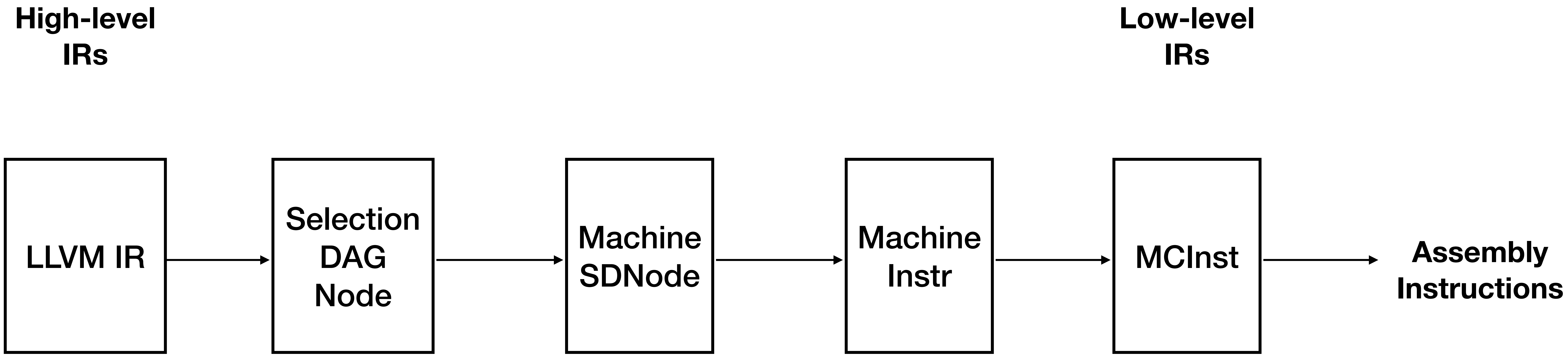
LLVM Intermediate Representation

```
def foo(a b) a*a + 2*a*b + b*b;
Read function definition:
define double @foo(double %a, double %b) {
entry:
  %multmp = fmul double %a, %a
  %multmp1 = fmul double 2.000000e+00, %a
  %multmp2 = fmul double %multmp1, %b
  %addtmp = fadd double %multmp, %multmp2
  %multmp3 = fmul double %b, %b
  %addtmp4 = fadd double %addtmp, %multmp3
  ret double %addtmp4
}
```

- Each instruction has a clear meaning
- Control flow or data flow information embedded
- Data types encoded

https://llvm.org/docs/tutorial/MyFirstLanguageFrontend/LangImpl03.html

LLVM Intermediate Representation(s)



Compilers typically use many IRs through out code generation lifetime

https://eli.thegreenplace.net/2012/11/24/life-of-an-instruction-in-llvm

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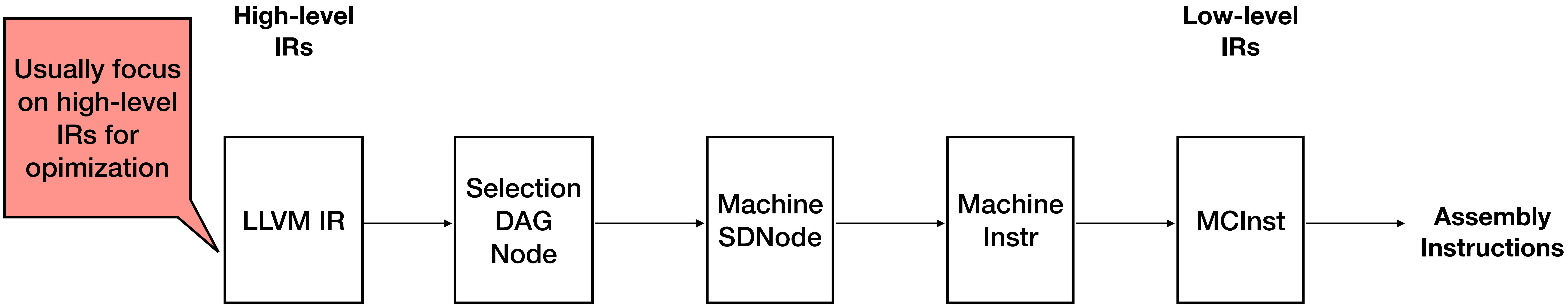

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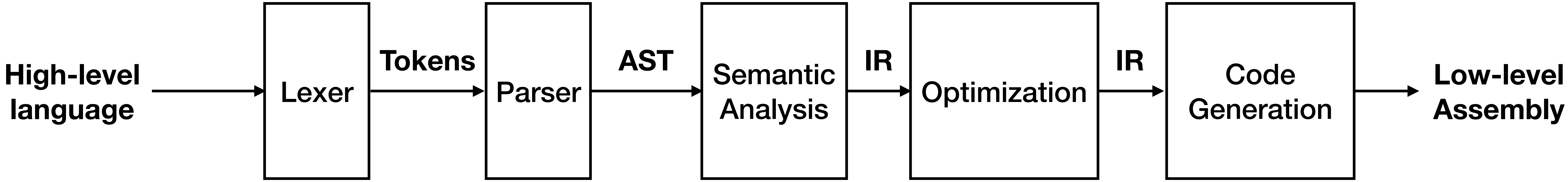
Finishing Up!



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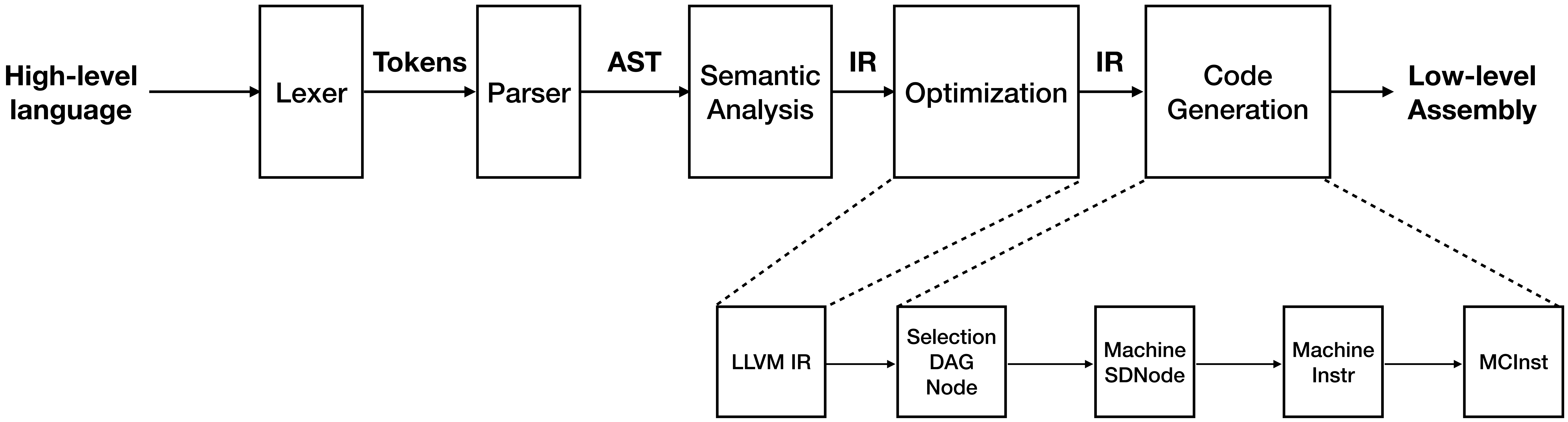
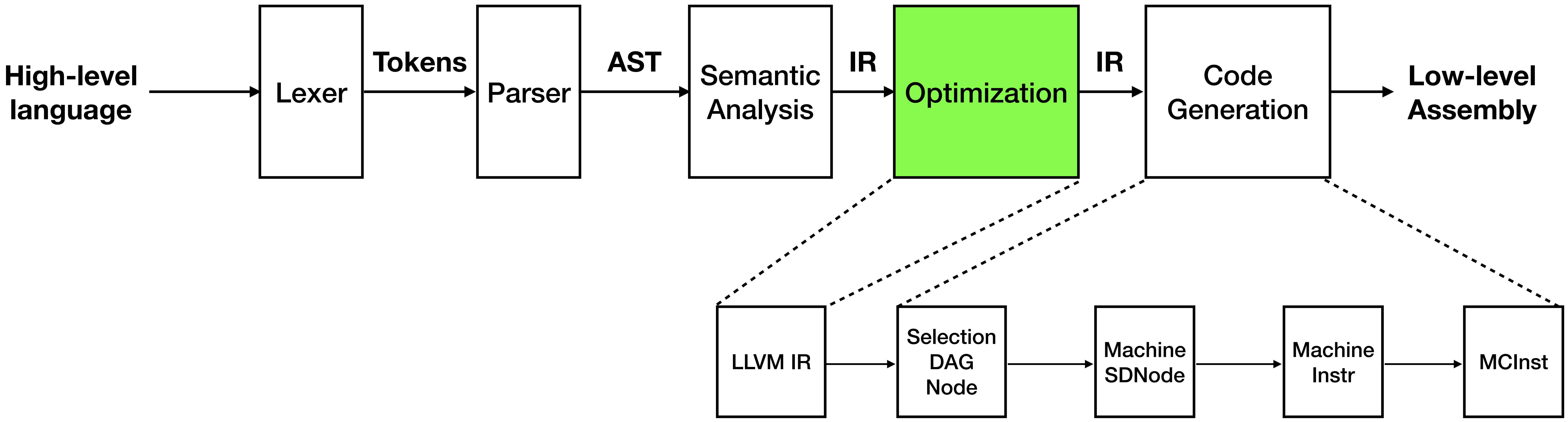


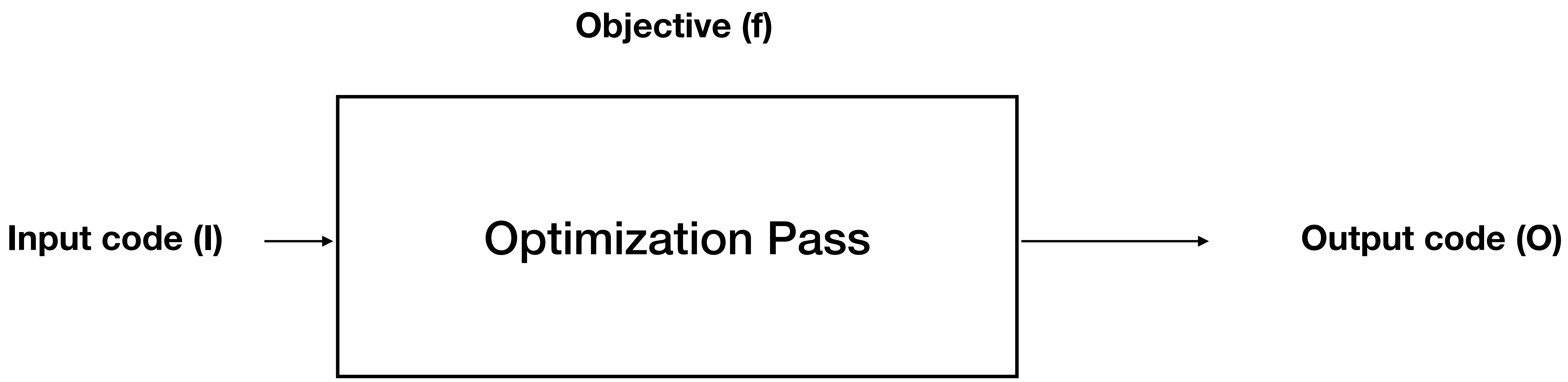
Wait we are just starting!



Code Optimization

- We are going to spend most time on this in this course
- Usually performed as IR to IR transformations
- Optimizes for an objective or multiple objectives: `f(code)`
  - Runtime
  - Memory footprint
  - Energy consumption
  - Code Size

Two types of Optimizations



Goal : `f(O) > f(I); where > means better`

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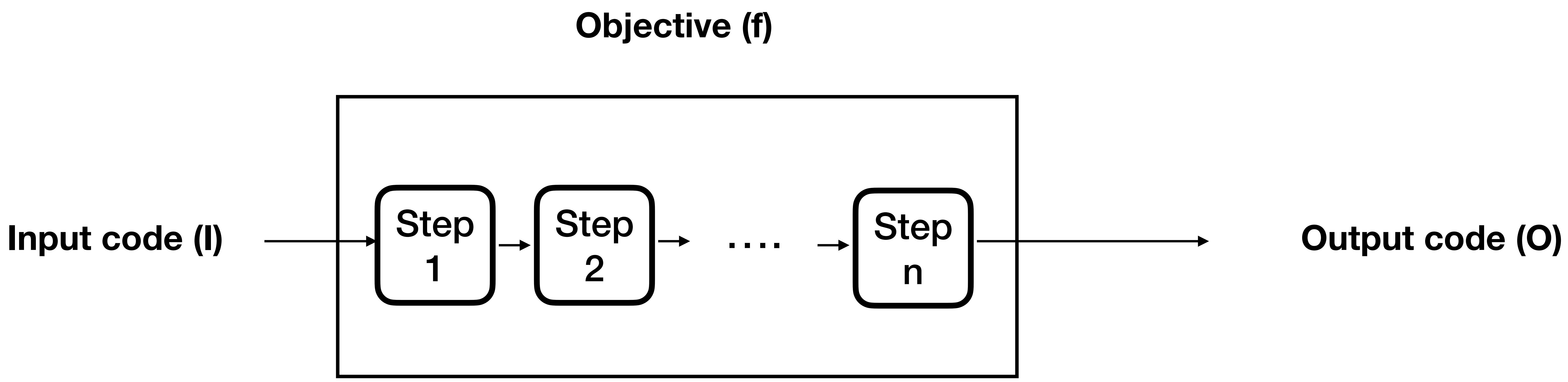

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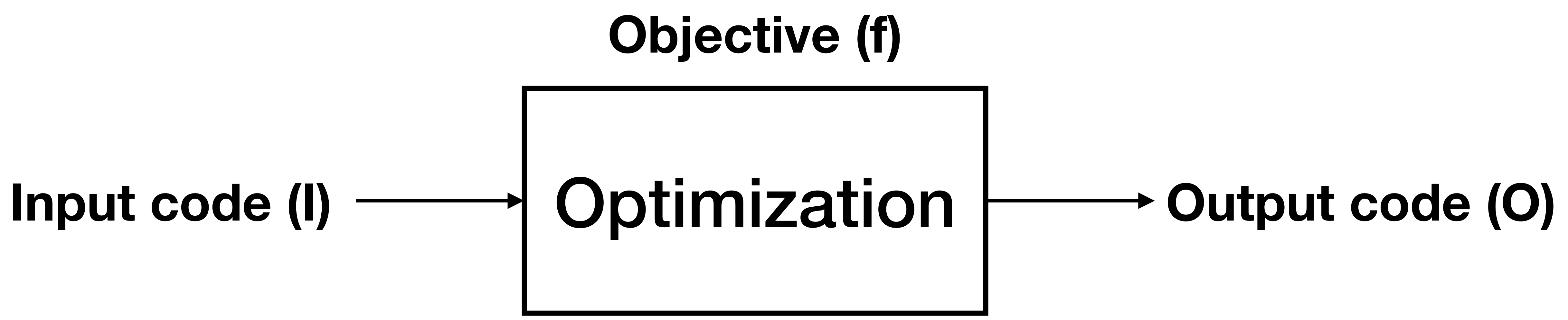


`Type I`

- Steps are always Profitable
  `f(O) > f(I)`
- Mostly independent

Dead Code Elimination, Constant Folding, Peephole Optimizations …….

`Type II`

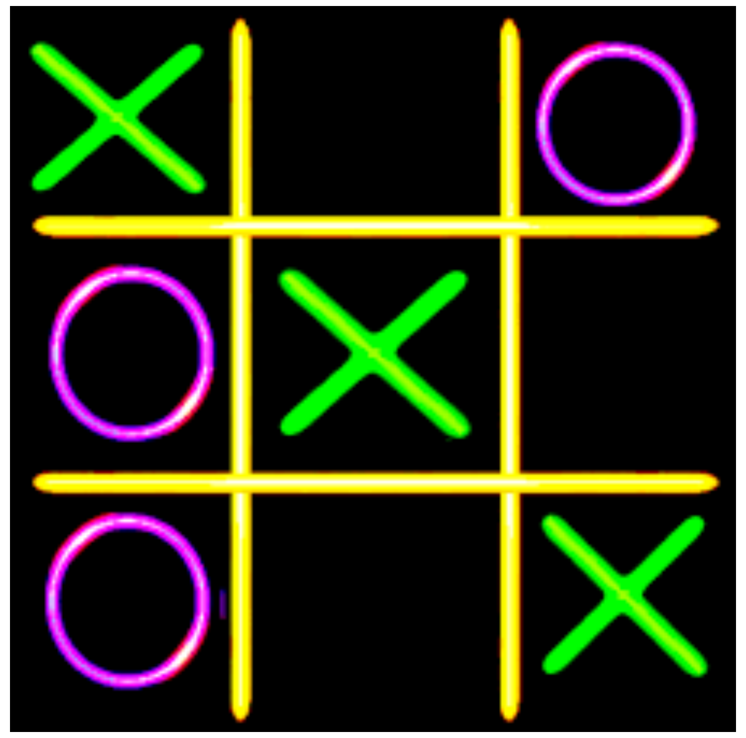
- Steps may not lead to global profitability
  `f(O) > f(I) ??`
- Mostly mutually-exclusive

Loop fusion, fission, unrolling, vectorization, parallelization…….

Gaming Analogy

`Type I`

Known strategy to at least draw
Newell and Simon (1972)



Tic-Tac-Toe

`Type II`

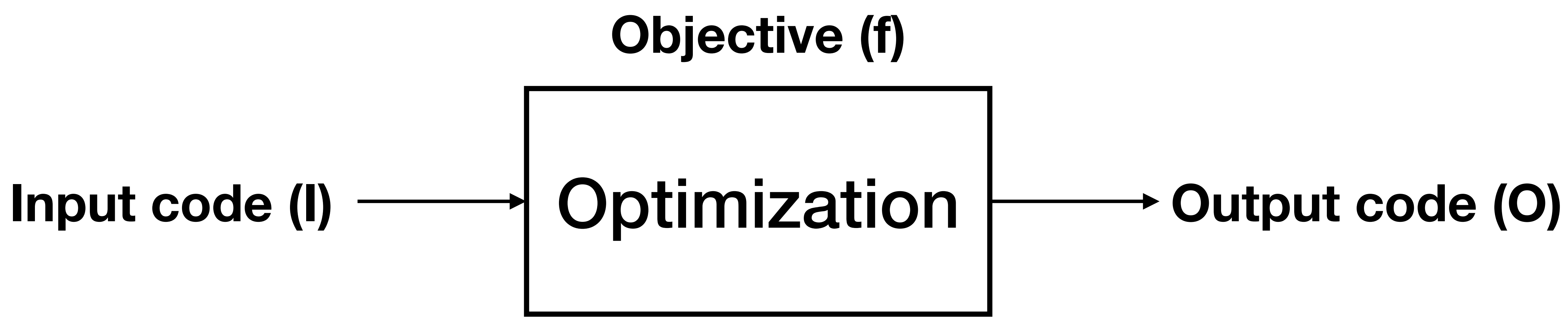
Do not know if a move will be profitable immediately

Chess

That's why it is highly competitive!!

https://onlinelibrary.wiley.com/doi/abs/10.1207/s15516709cog1704_3

Two types of Optimizations



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Dead Code Elimination

```c
int foo(void)
{
  int a = 24;
  int b = 25;
  int c;
  c = a * 4;
  return c;
  b = 24;
  return 0;
}
```

https://en.wikipedia.org/wiki/Dead_code_elimination

Dead Code Elimination

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Always a good idea to
get rid of unwanted statements

Always a good idea to
get rid of unreachable code

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Always a good idea to get rid of unwanted statements

Always a good idea to get rid of unreachable code

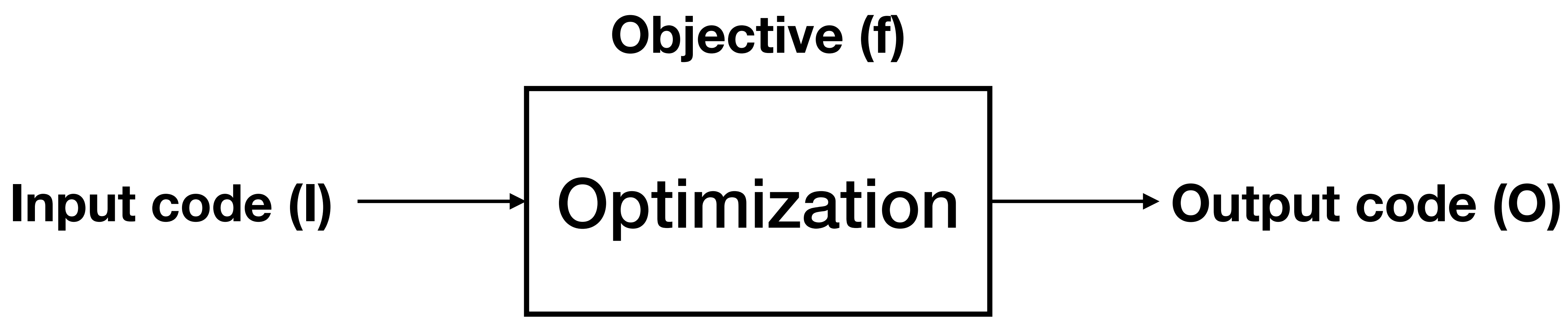
→

```
int foo(void)
{
  int a = 24;
  int c;
  c = a * 4;
  return c;
}
```

No optimization decision making needed!

https://en.wikipedia.org/wiki/Dead_code_elimination

Two types of Optimizations



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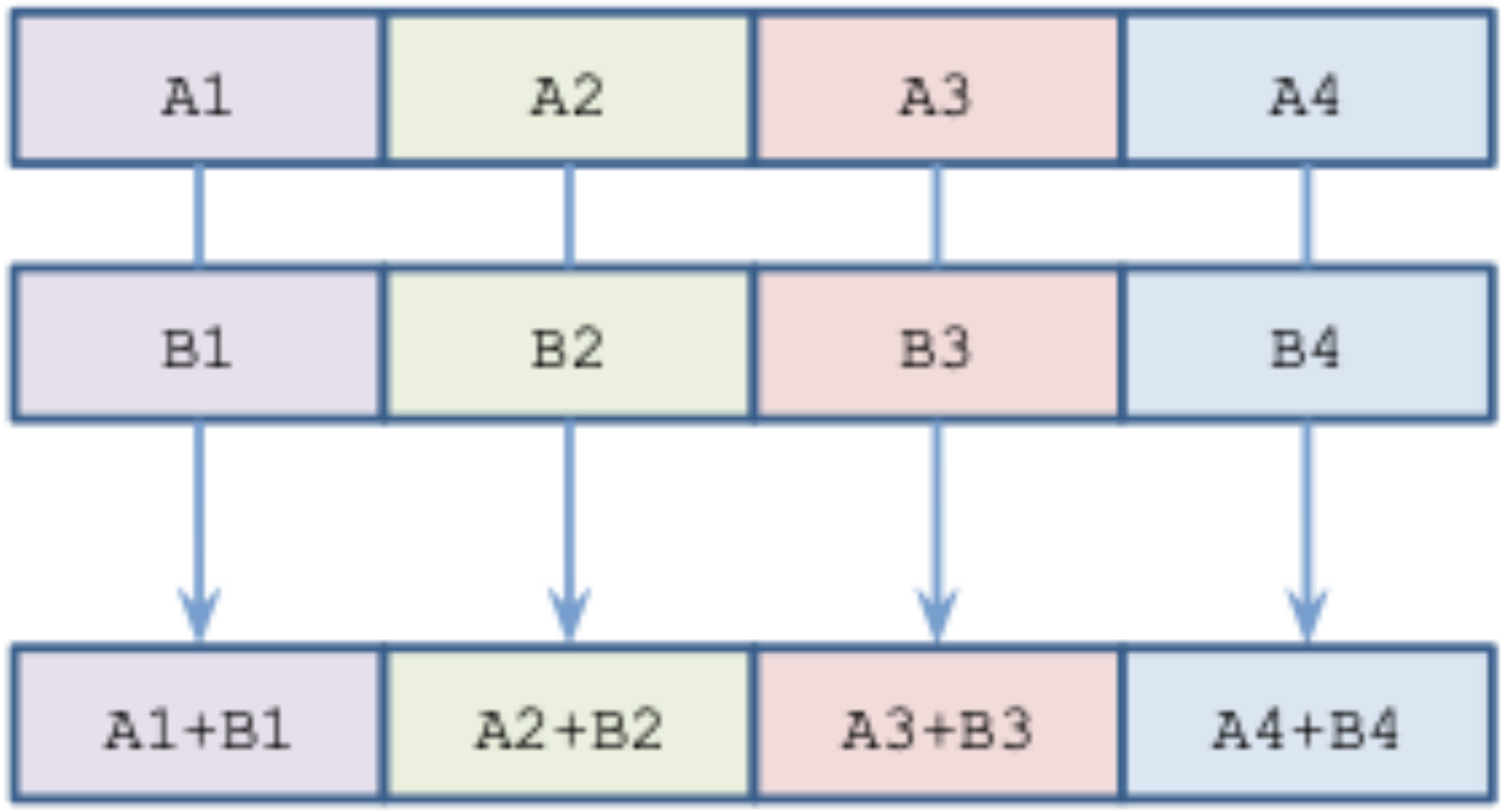
Hardware Vector Units



Single **I**nstruction **M**ultiple **D**ata execution

Intel Vector-ISA Generations

32-bit scalar only	**64**-bit vector (MMX)	**128**-bit vector (SSE2)	**256**-bit vector (AVX2)	**512**-bit vector (AVX512)
	1997	**2000**	**2011**	**2016**

Increase in bit-width

→

Diversity in Instruction Set

Vectorization

Independent and **Similar** statements can be vectorized

Scalar Code

Vector Code
Single **I**nstruction **M**ultiple **D**ata (SIMD)

```
a[0] = b[0] + c[0]
a[1] = b[1] + c[1]
```

Vector Packs

→

```
{a[0],a[1]} = {b[0],b[1]} + {c[0],c[1]}
```

Vectorization

- Are Vectorization opportunities always independent?
- Are Vectorization opportunities always globally profitable?

```
A1 = L[0] + L[4]
A2 = L[3] + L[5]
A3 = L[1] + L[5]
```

Assume that the vector unit can only execute 2 instructions at a time

What are **all** vectorization possibilities?

Vectorization

- Are Vectorization opportunities always independent?
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A1 = L[0] + L[4]
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`{A1,A2}`

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{A1,A2}
{A1,A3}
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Vectorization

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Vectorization

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```

Assume that the vector unit can only execute 2 instructions at a time

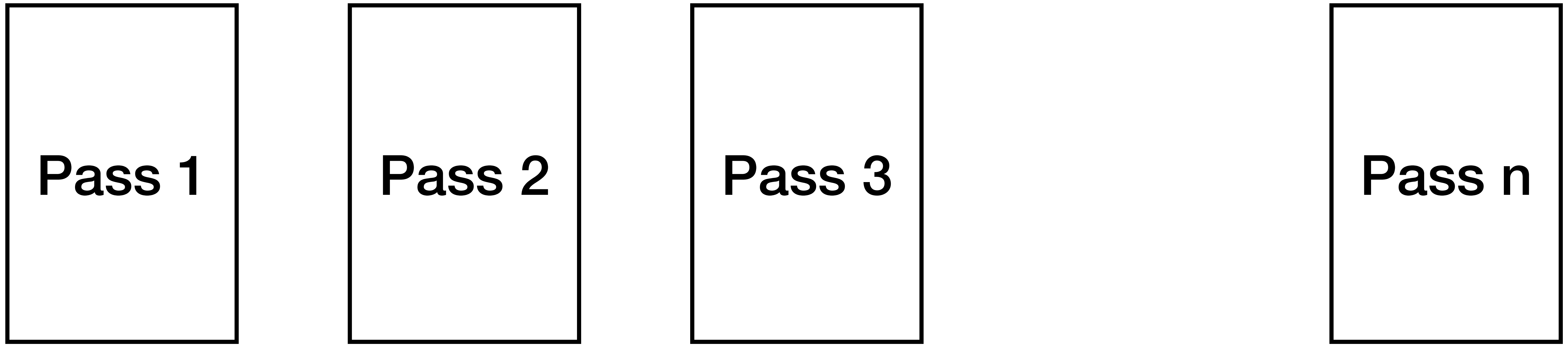
What are **all** vectorization possibilities?

```
{A1,A2}
{A1,A3}
{A2,A3}
```

How to make step decisions?

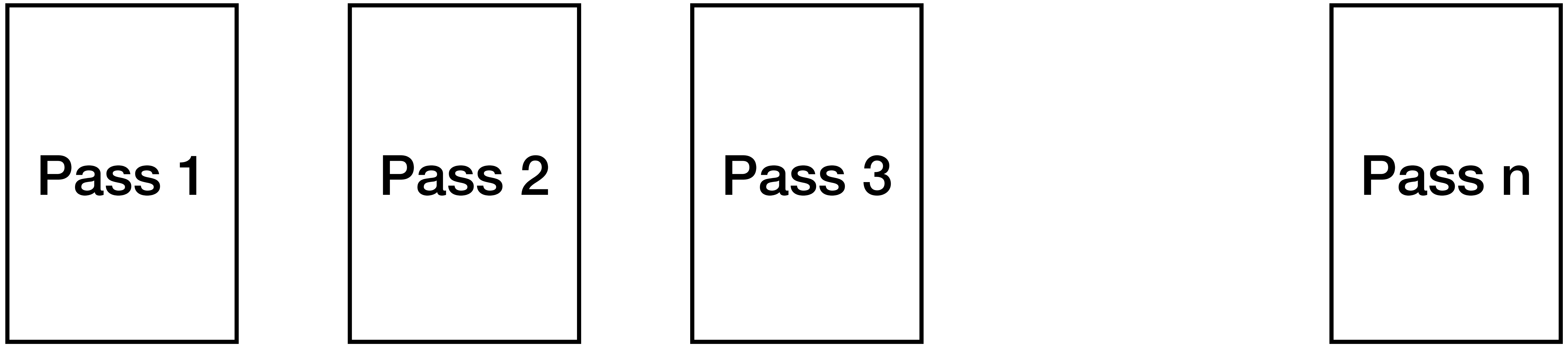
- Enumerate all possible choices and select the most profitable?
- **Intelligent Search**
  - Meta Optimization: improving compiler heuristics with machine learning (PLDI 2003)
- **Learned Optimizations**
  - Compiler Auto-vectorization using Imitation Learning (NeurIPS 2019)
  - NeuroVectorizer: End-to-End Vectorization with Deep Reinforcement Learning (CGO 2020)

Multiple Optimization Passes



How do we compose these passes?

Multiple Optimization Passes



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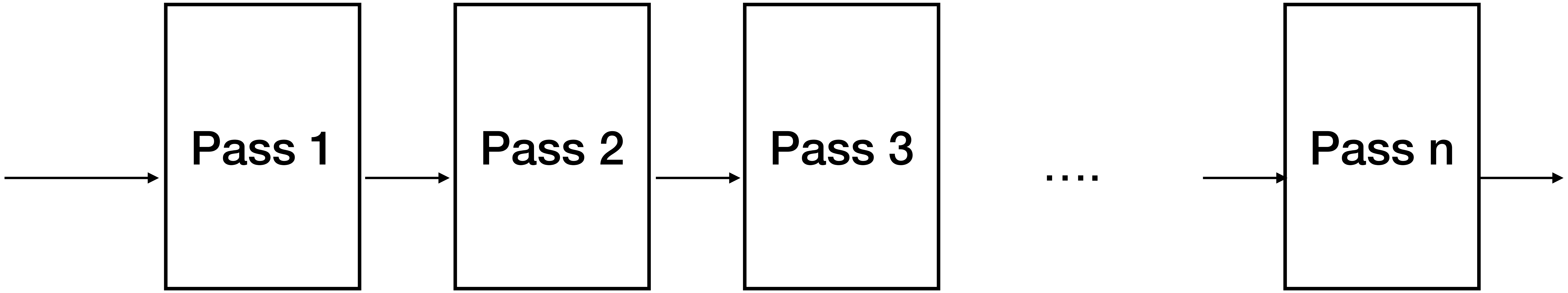
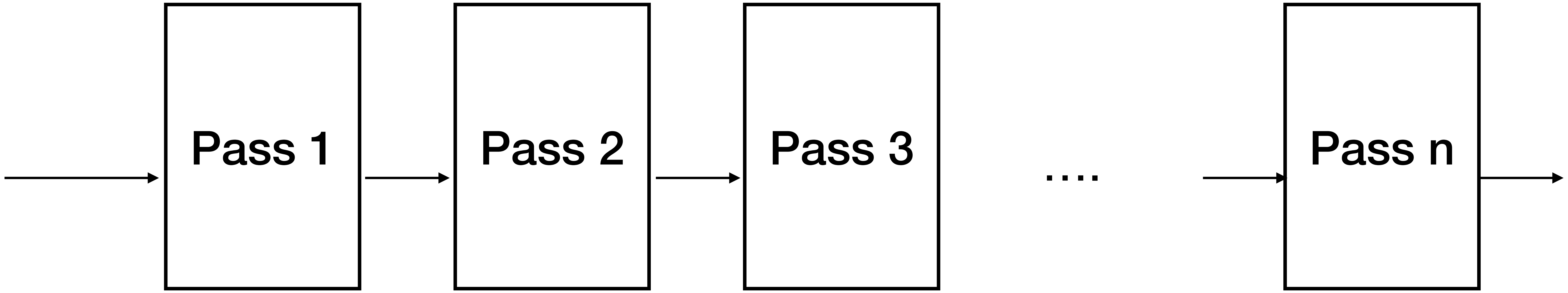


How do we compose these passes? Run them in sequence

Multiple Optimization Passes



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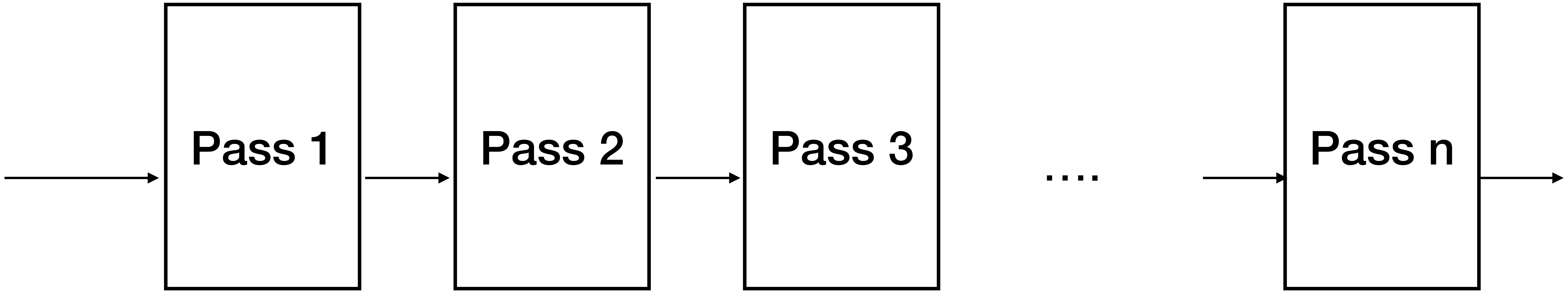
Faces the same challenges at Type II Optimizations:
Now passes are the steps

Phase Ordering Problem

Multiple Optimization Passes



How do we compose these passes? Run them in sequence

Faces the same challenges at Type II Optimizations:
Now passes are the steps

Phase Ordering Problem (RL solution in the reading list)

Next Lecture

- Anatomy of a type II compiler optimization pass
- Exposing Tunable parameters
- DSLs and Domain Specific Optimizations
- Examples on Learned Optimization and Cost Models

How to select papers?

- Familiar with the subject area
- Read the contributions and the motivation. Sounds Interesting?
- Not all papers are of equal difficulty to read
  - Difficulty of the paper taken into account during grading
  - Dependency of the paper on related work also taken into account

Any Questions?