# CS 598CM: ML for Compilers and Architecture

Instructor: Charith Mendis

ILLINOIS

# Brief Announcements

- Recordings and Zoom
- **Pre-requisites:** CS 426, CS 433, CS 421
  - I will try to give crash-courses like today
  - Willing to learn as we go
- **Reading List:** After today's lecture
- **Paper Selections:** Due on September 7th; link will be live today

# Lecture 2: Compilers

**Crash-course + Optimizations**

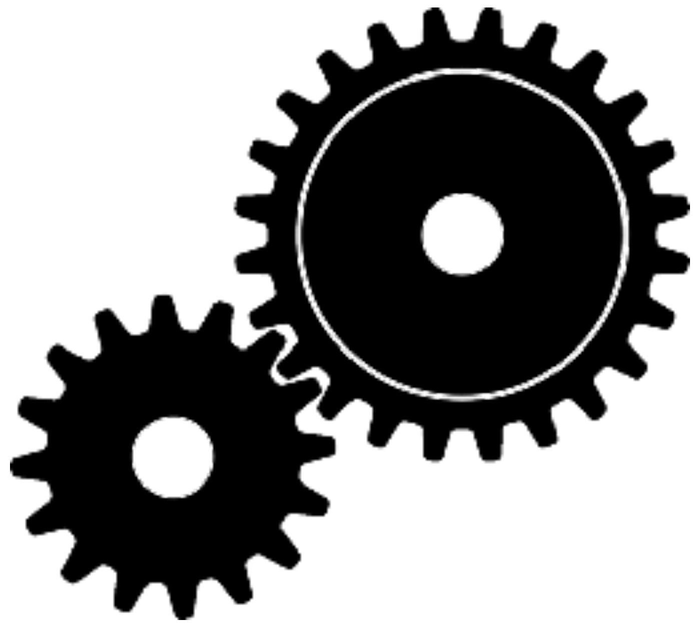
# Compilers translate high-level languages to low-level machine code

**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**



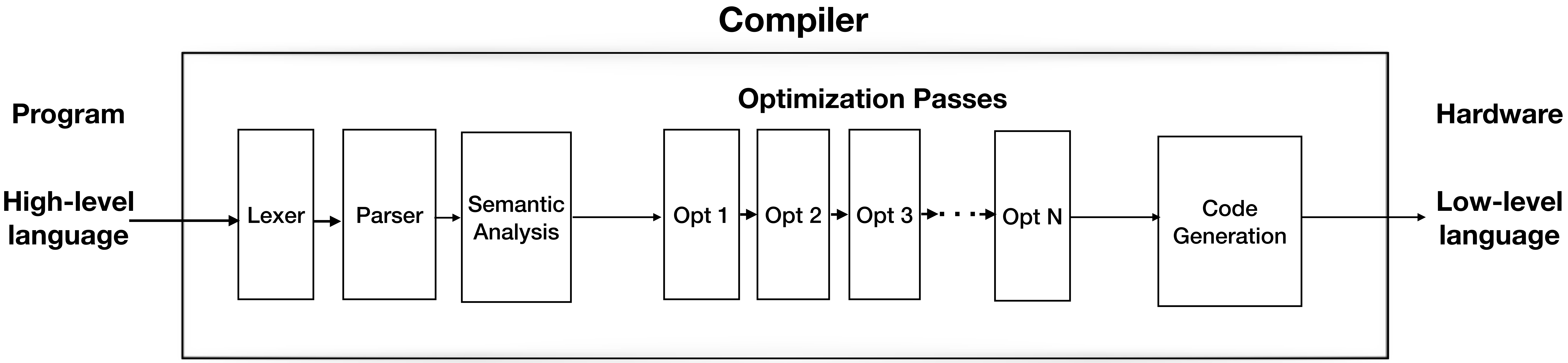
**Hardware**

```
          ......
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
          ......
```

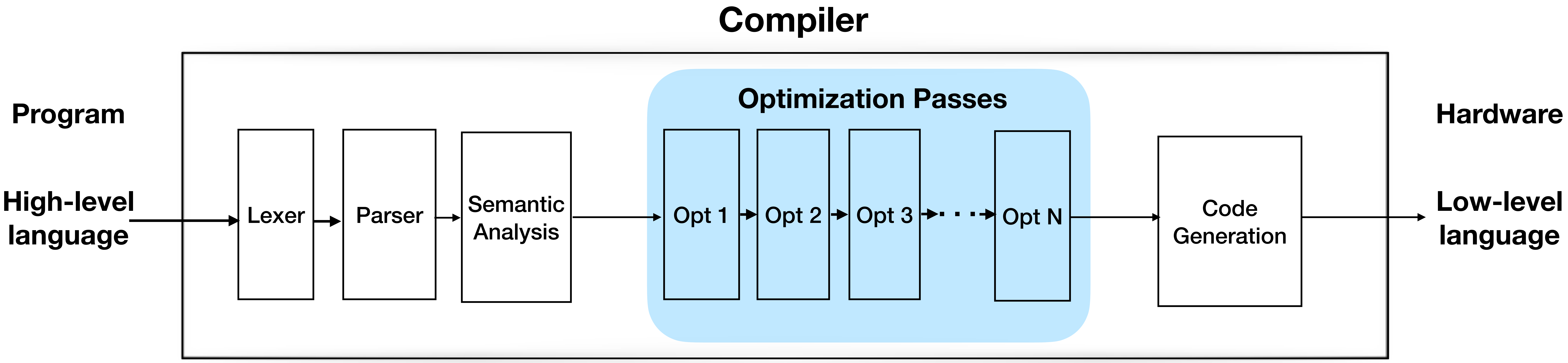
Low-level assembly language

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

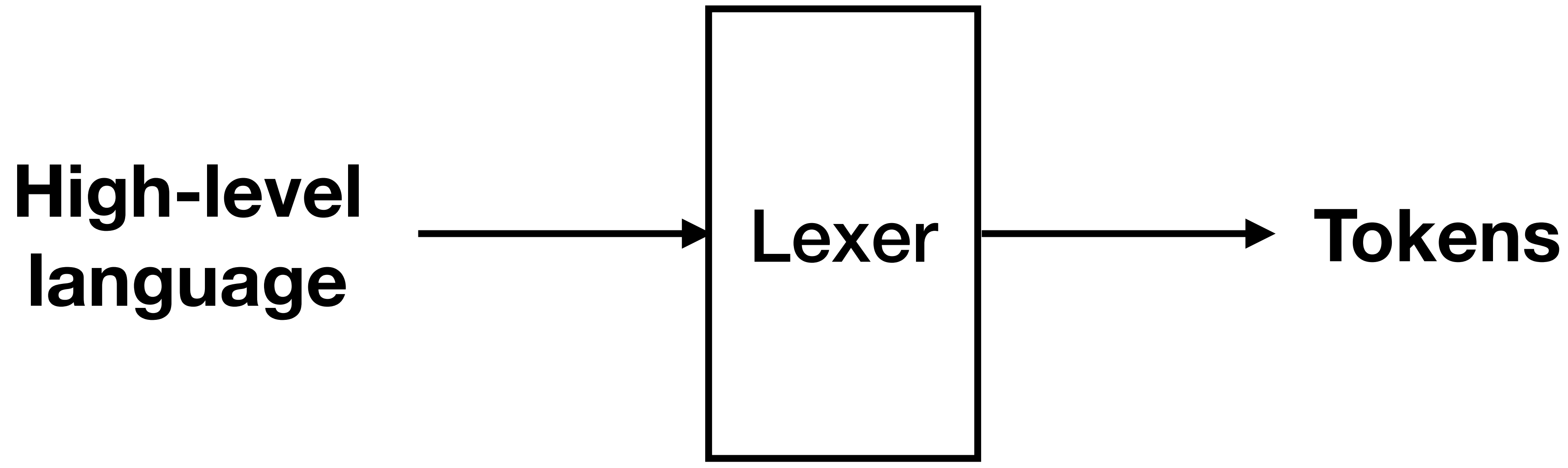
# Stages of a Compiler



# Stages of a Compiler



# Lexer




List or stream of strings with syntactic meaning

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

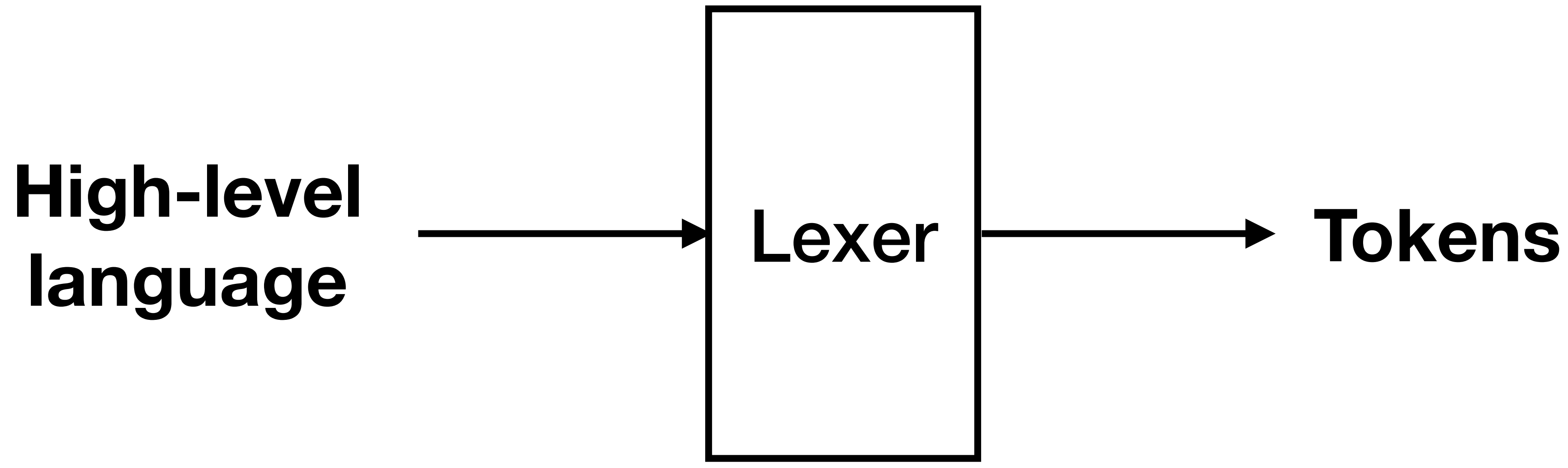
<for> <(> <int> … <A> <[> <i> <]> …

Keywords

Separators

Identifiers

# Lexer




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

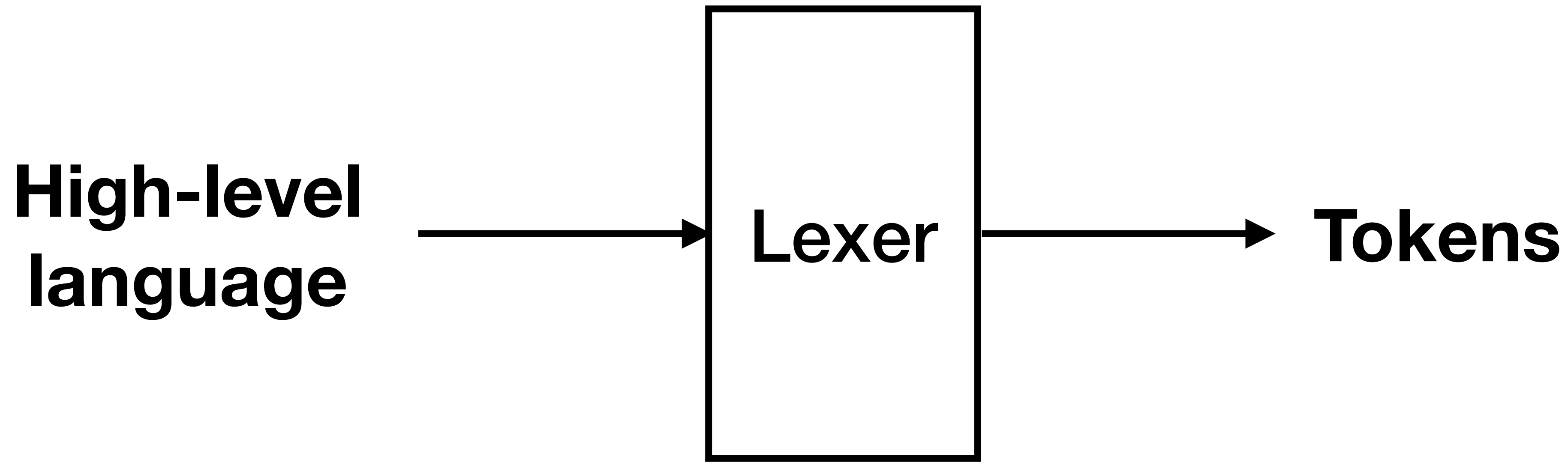
```
for (int i= 0; i <100; i++){
  A[i] = A[i+1] + 1;
}
```

```
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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for (int i= 0; i <100n; i++){
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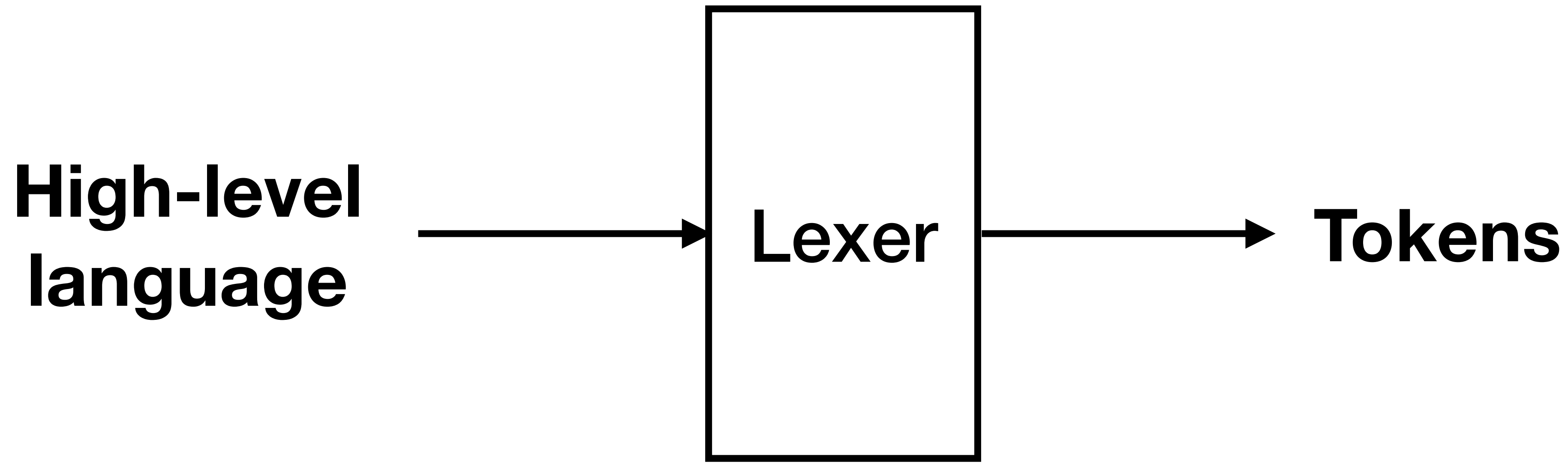
# Lexer

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

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for (int i= 0; i <100; i++){
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for (int i= 0; i <100n; i++){
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}
```
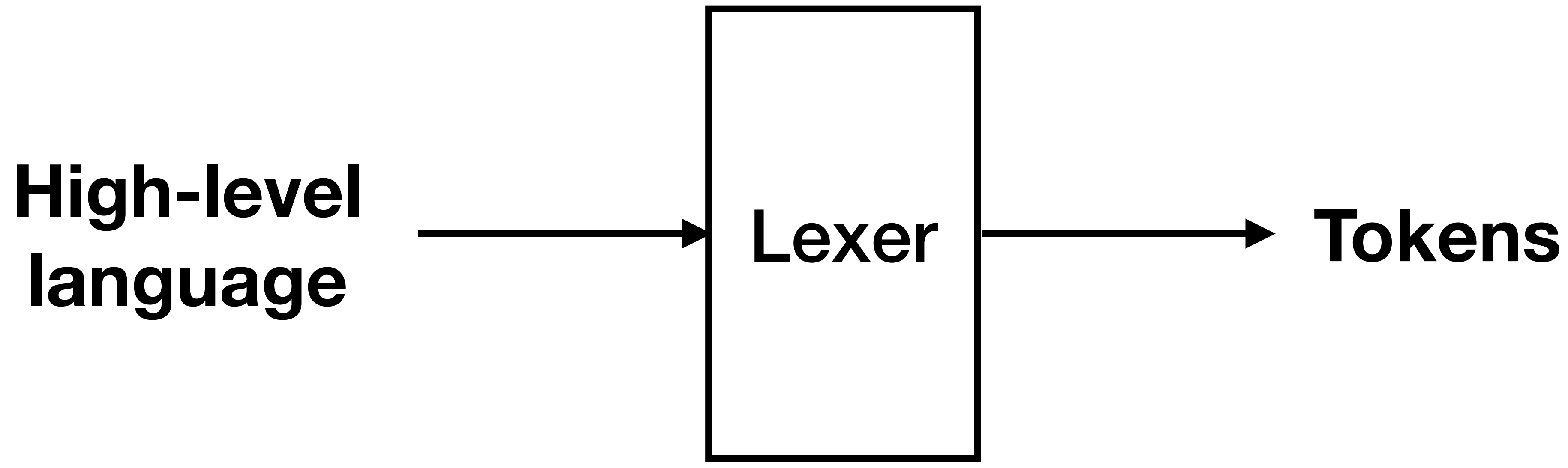

# Lexer

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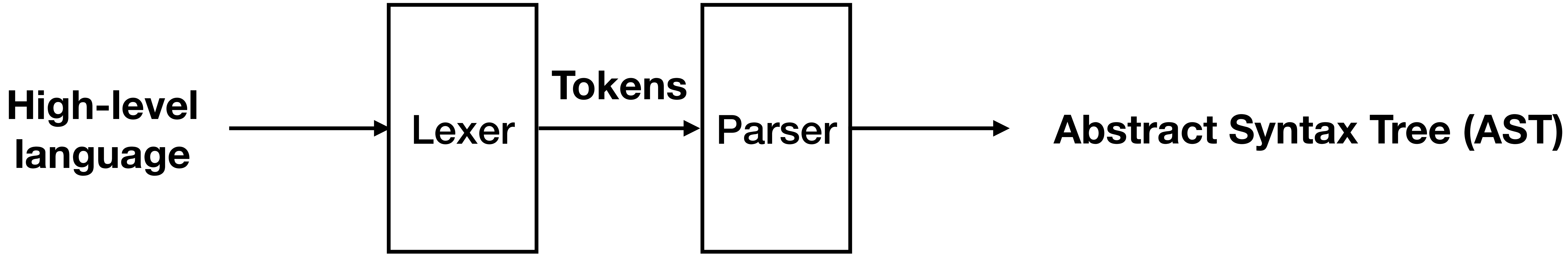
for (int i= 0; i <100; i++){
  A[i] = A[i+1] + 1;
}
```

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

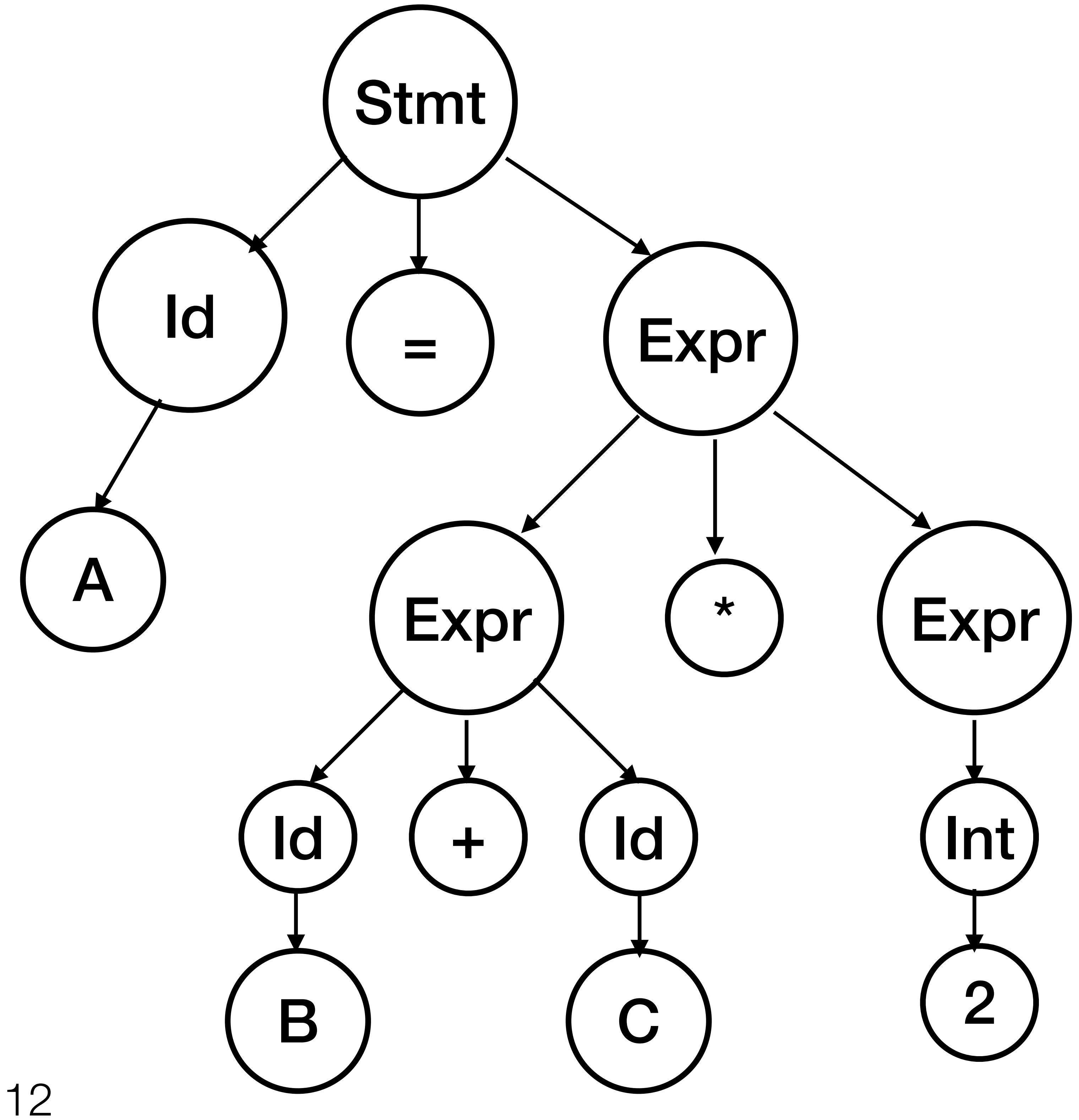
```
for (int i= 0; i <100; i++){
  A[i] = A[j+1] + 1;
}
```

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

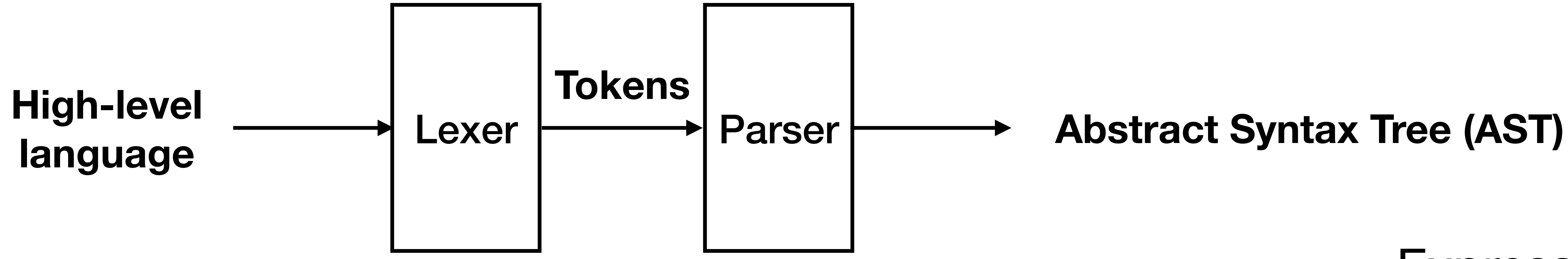
# Parser


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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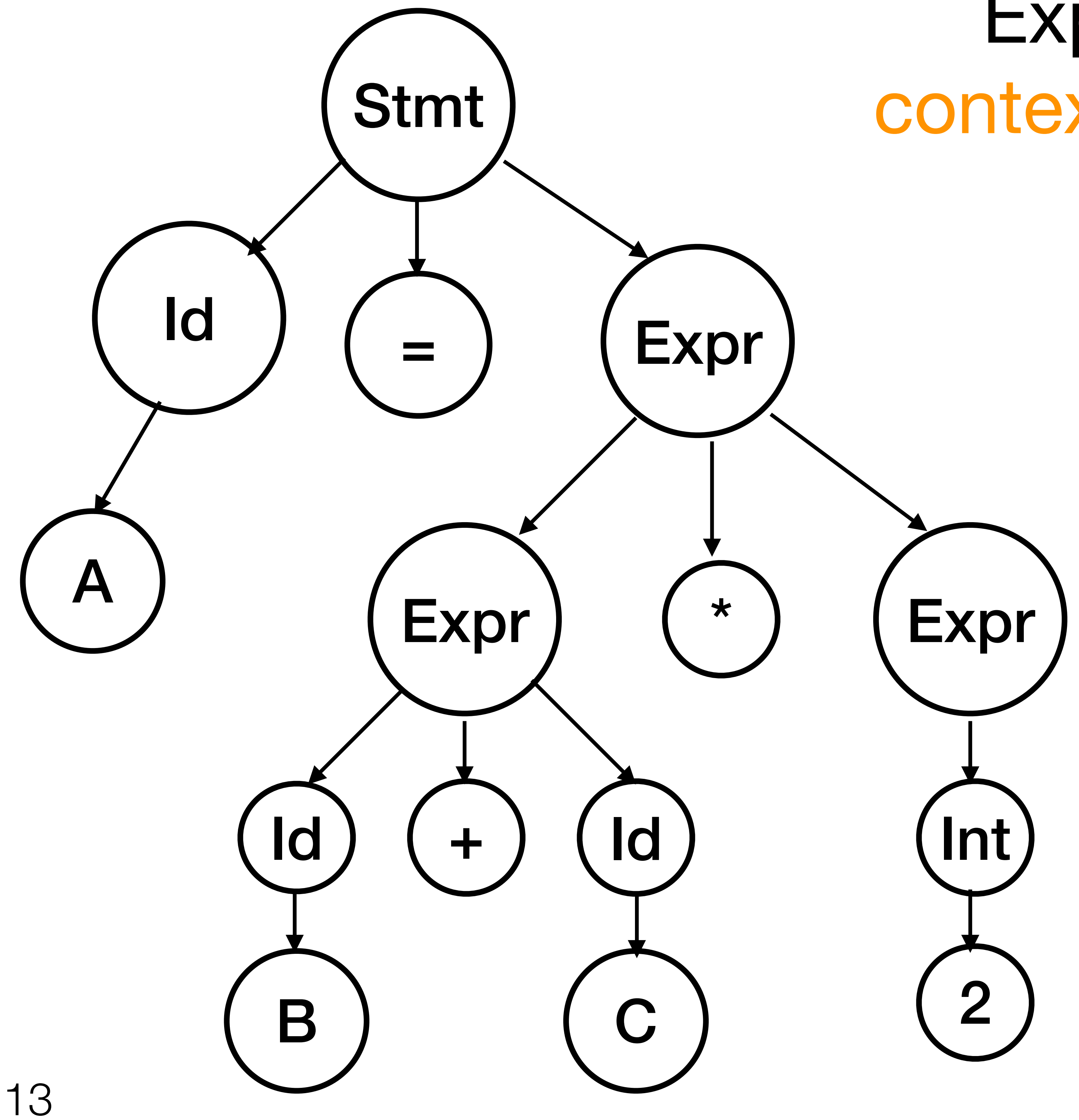
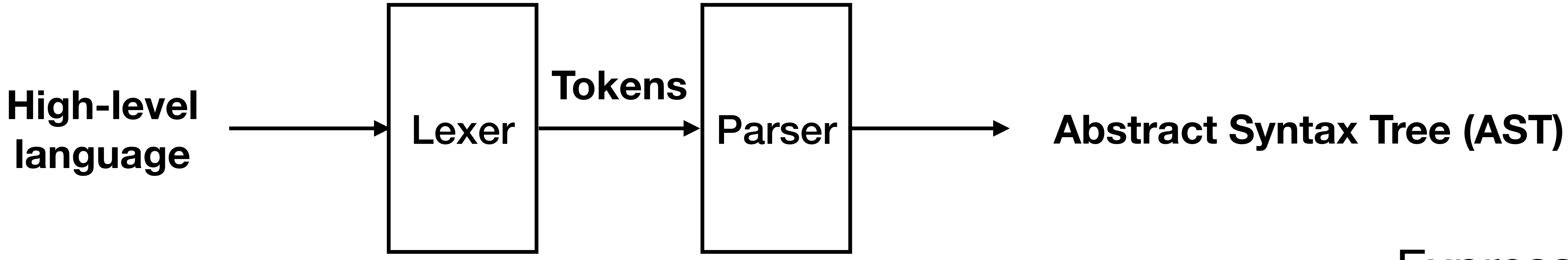



Expressed as a
context-free grammar

# Parser




Expressed as a context-free grammar

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A = (B + C) * 2;
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```

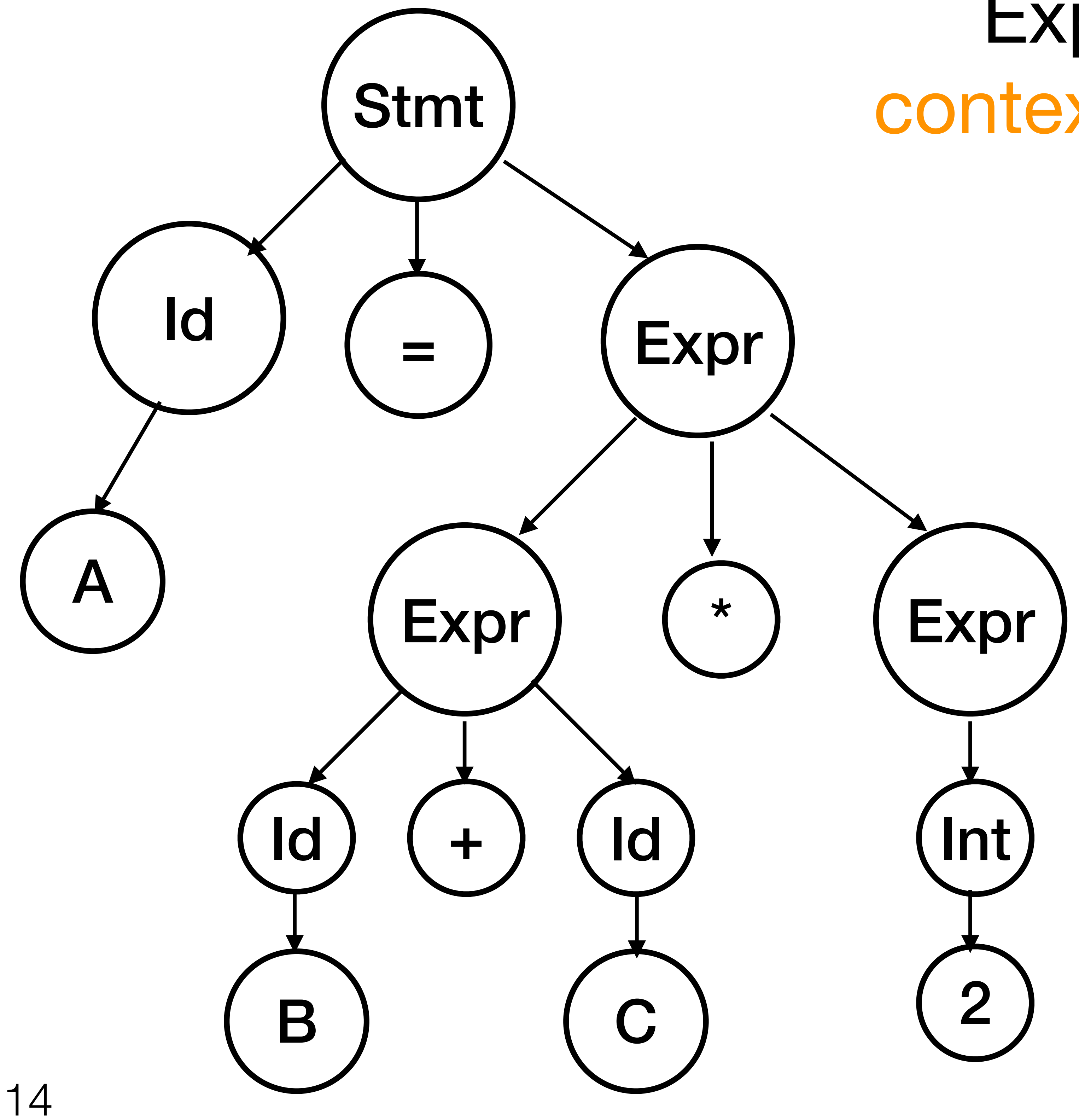

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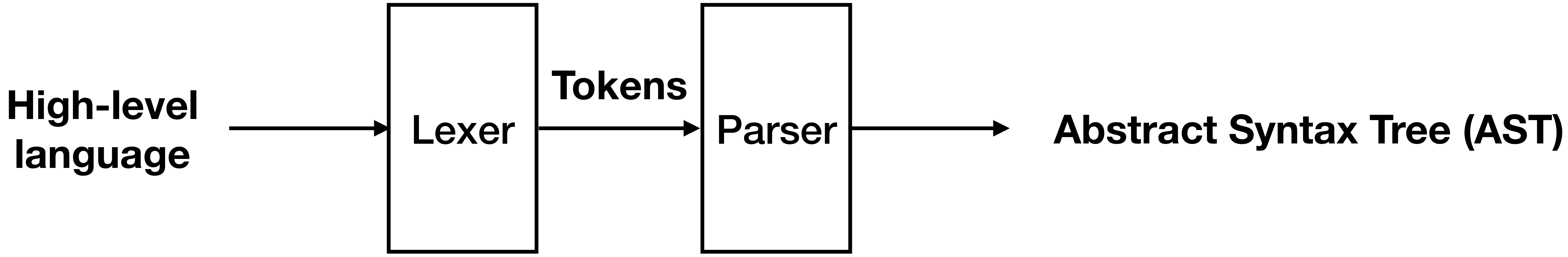
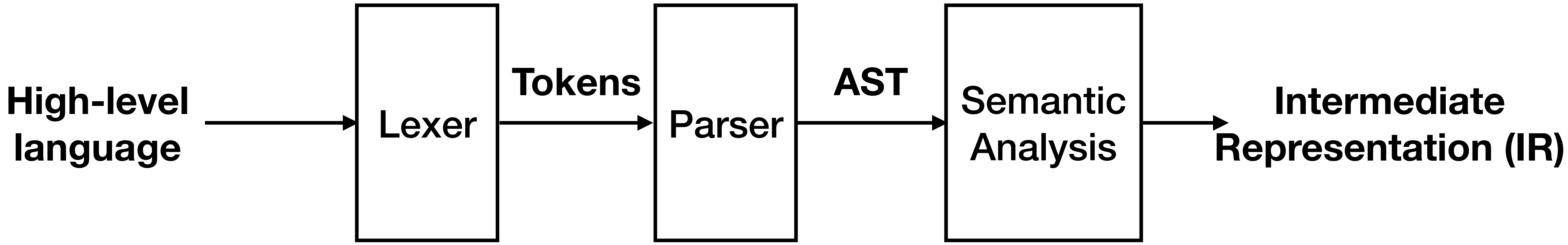


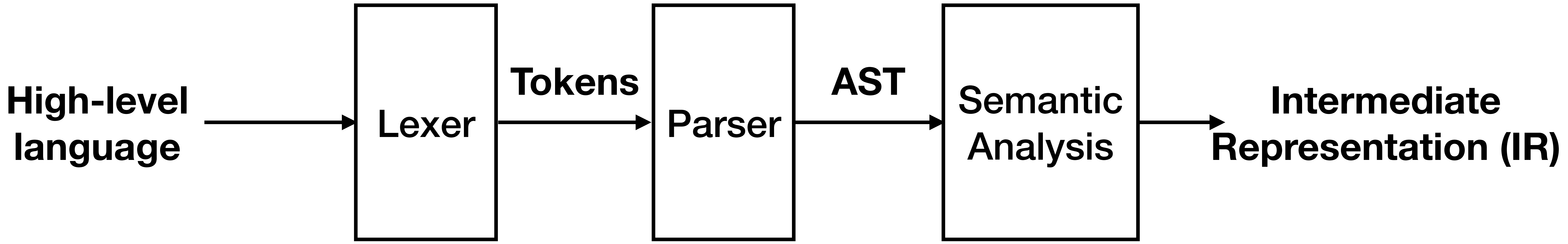

- Does not check if variables are defined
- Does not have scopes; variable bindings not defined
- Control flow or data flow information is not explicit

# 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!

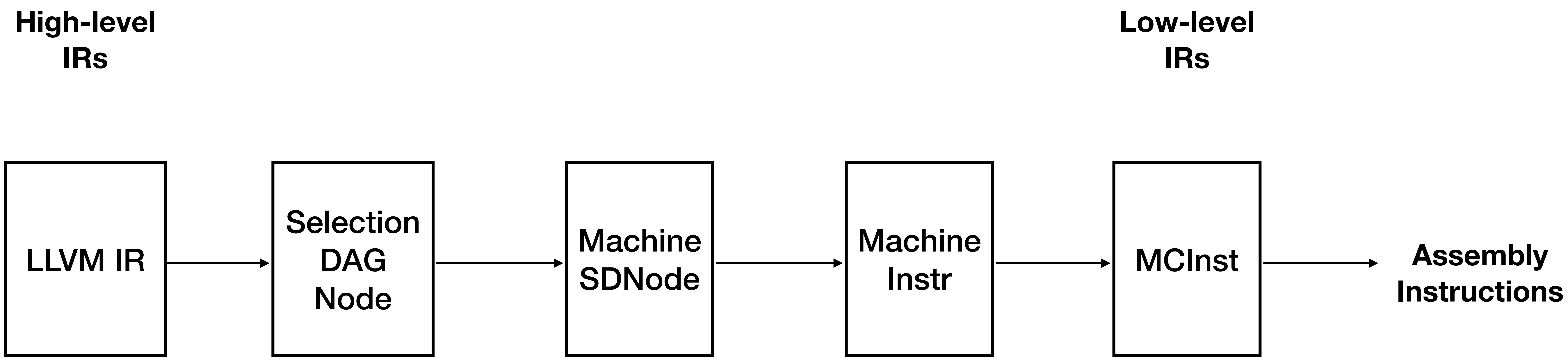
# LLVM Intermediate Representation

```
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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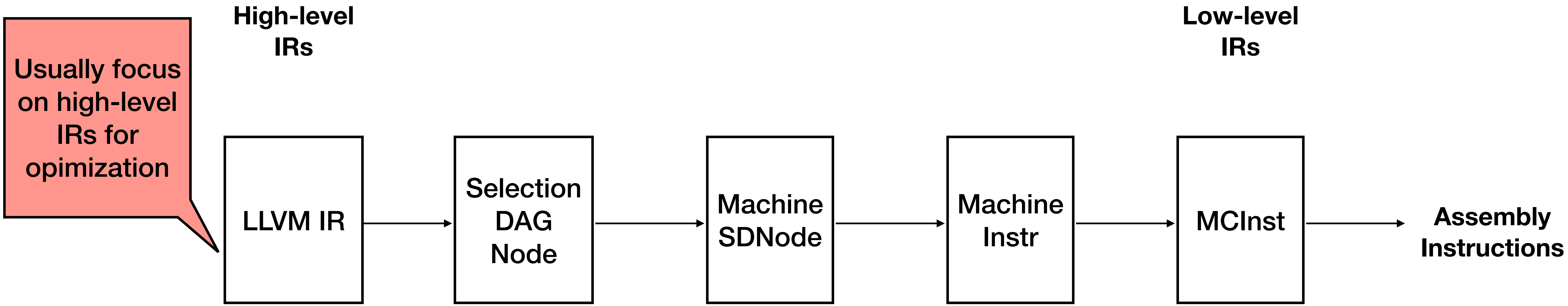


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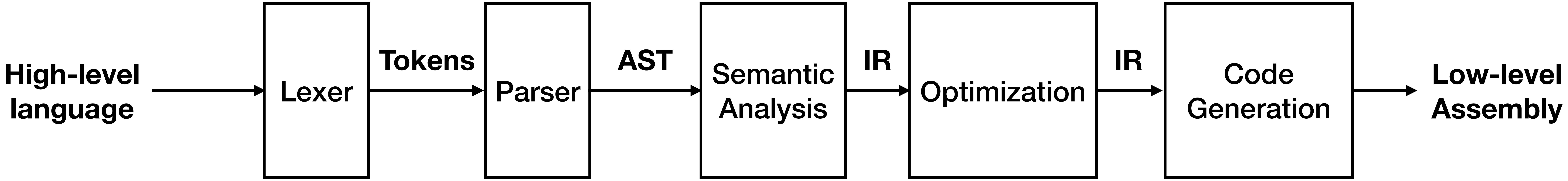
# Finishing Up!



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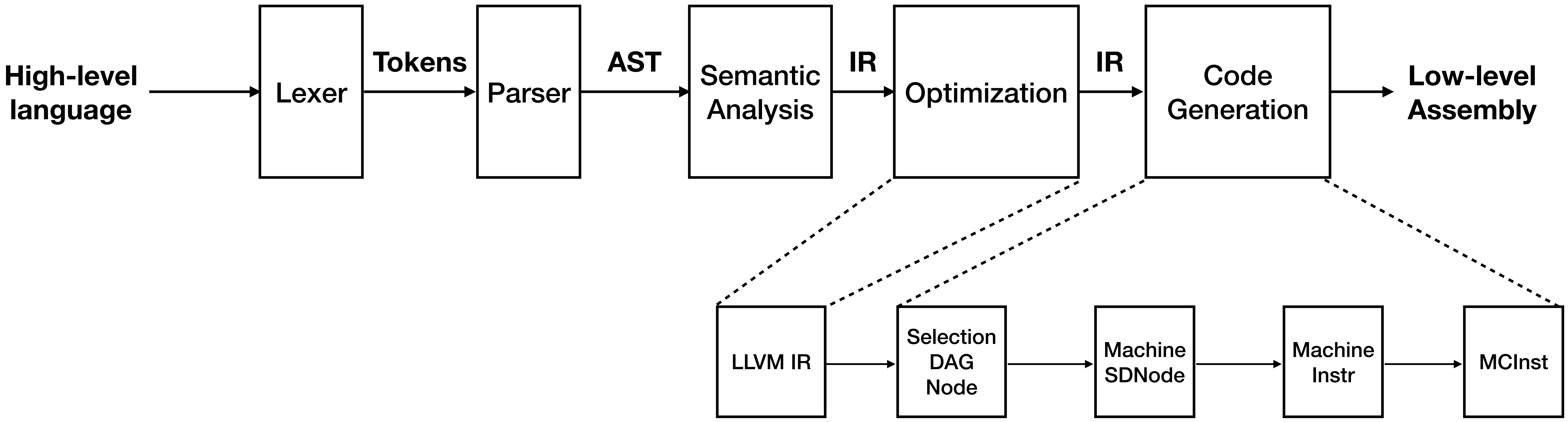
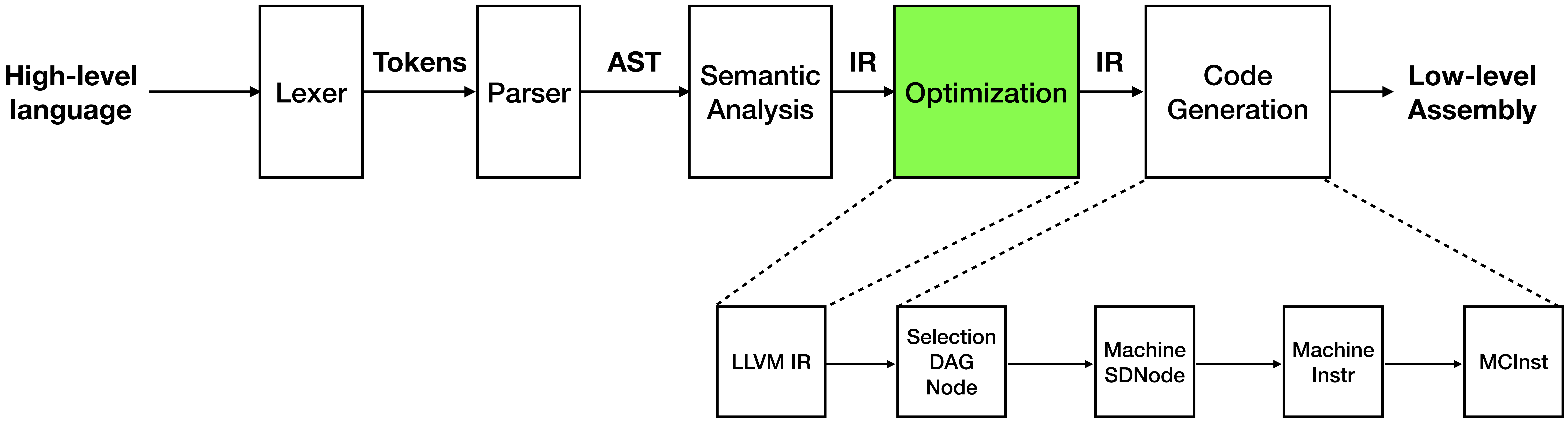


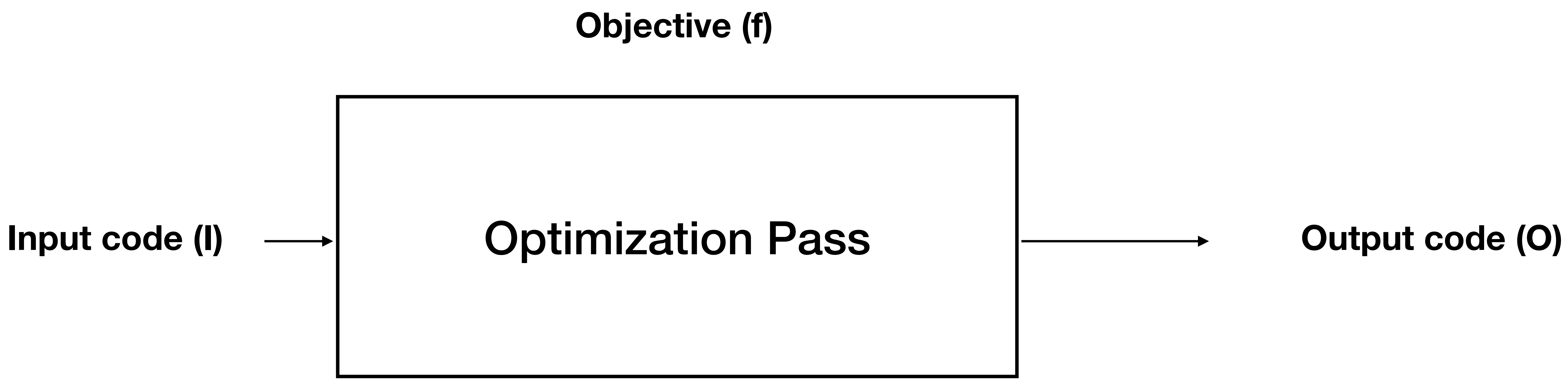
# Wait we are just starting!



# Code Optimization

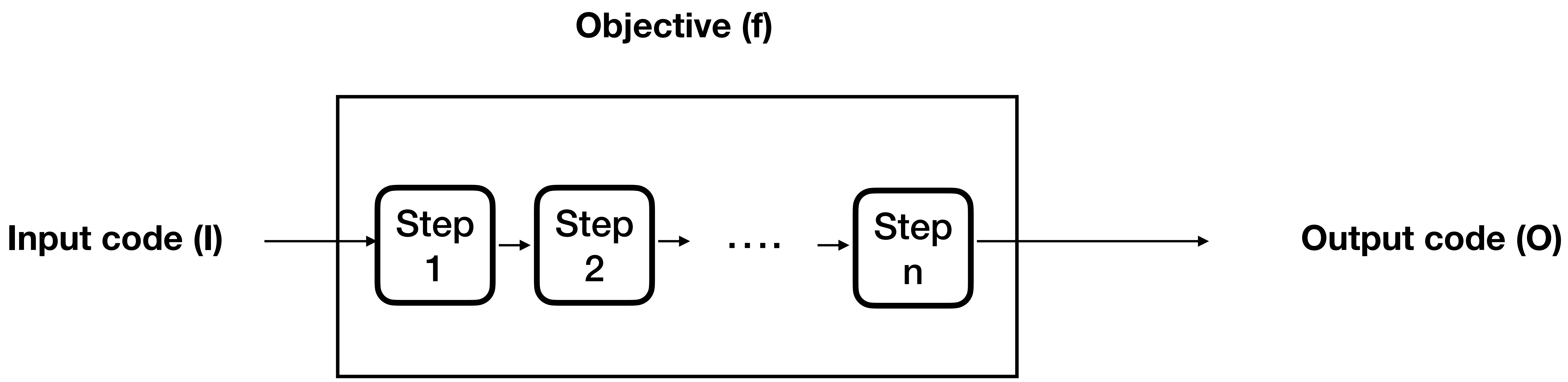
- We are going to spend most time on this in this course
- Usually performed as IR to IR transformations
- Optimizes for an objective or multiple objectives: `f(code)`
  - Runtime
  - Memory footprint
  - Energy consumption
  - Code Size

# Two types of Optimizations




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

# Two types of Optimizations

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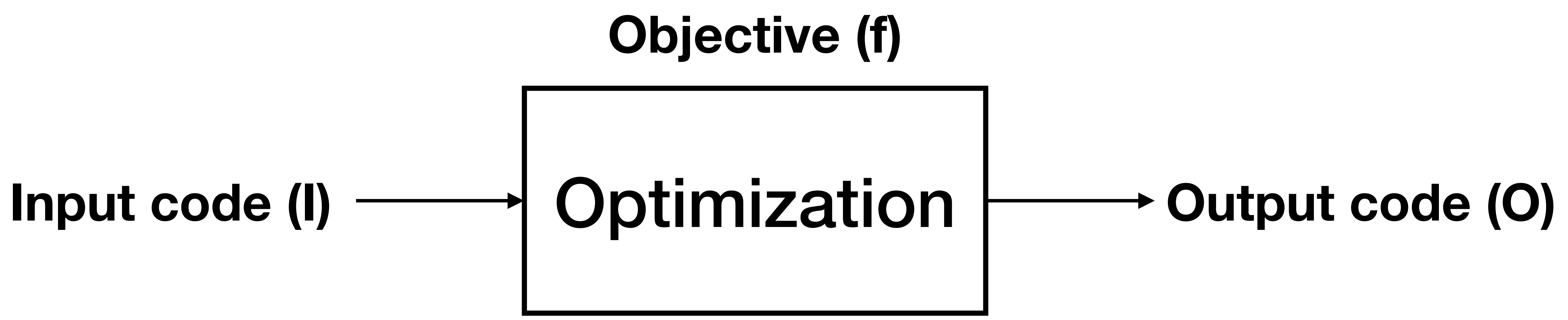



## `Type I`

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

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

## `Type II`

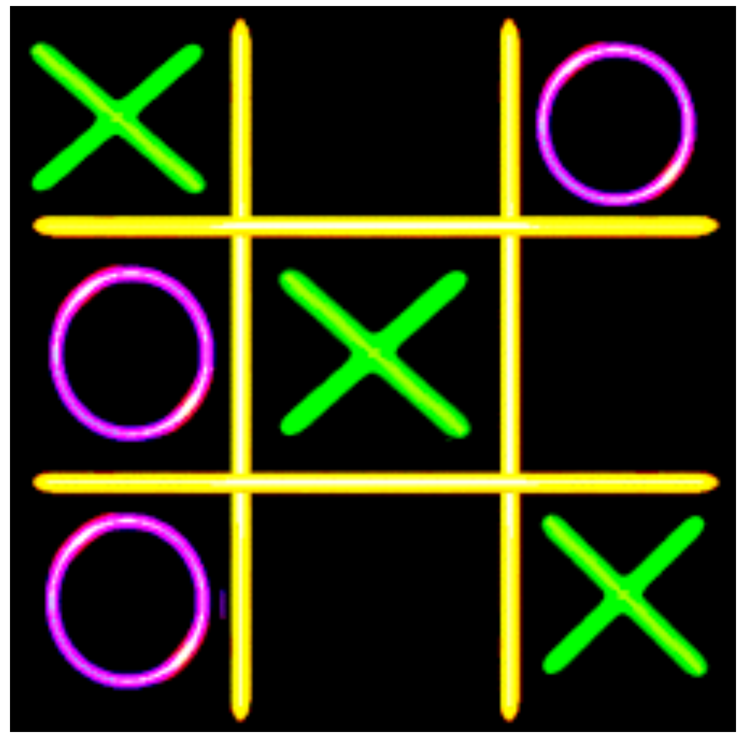
- Steps may not lead to global profitability
  `f(O) > f(I) ??`
- Mostly mutually-exclusive

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`

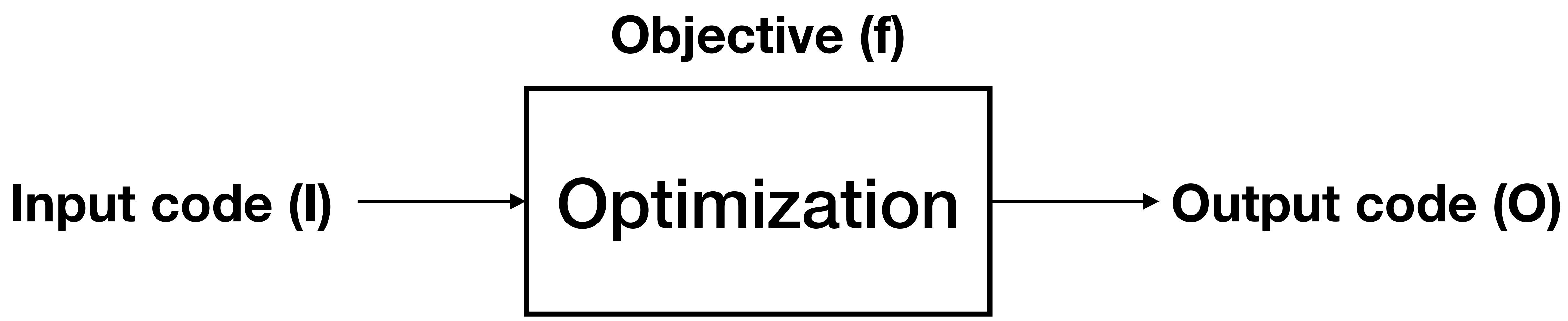
Do not know if a move will be profitable immediately

**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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Loop fusion, fission, unrolling,
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# Dead Code Elimination

```
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
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Always a good idea to get rid of unwanted statements

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→

```
int foo(void)
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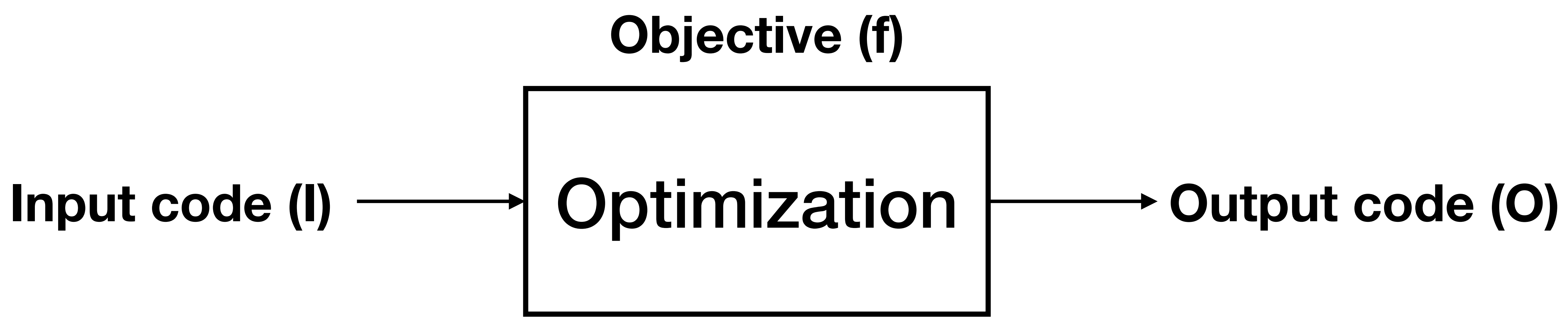
**No optimization decision making needed!**

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

# Two types of Optimizations

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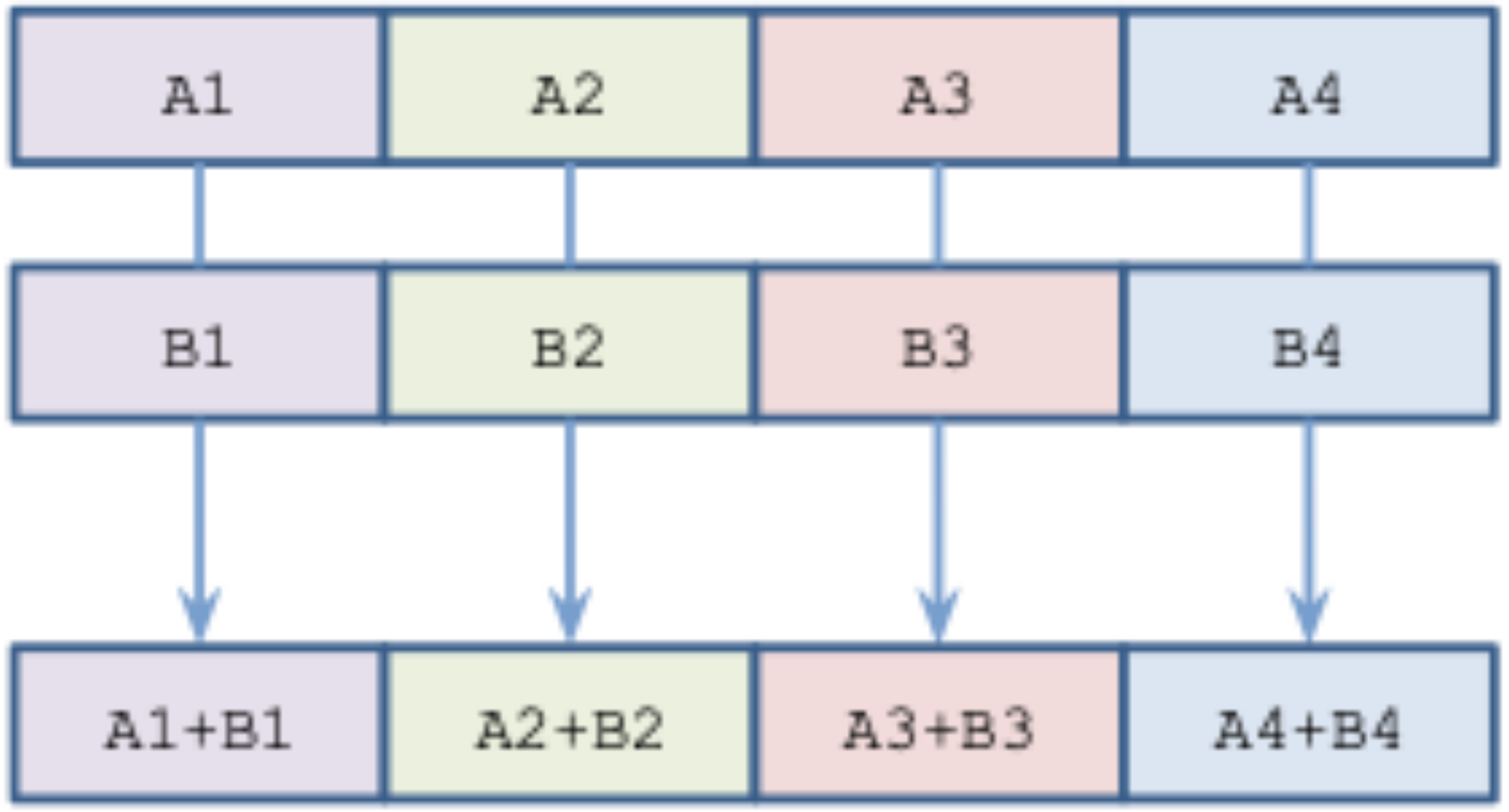
# Hardware Vector Units




**S**ingle **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

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

**Vector Packs**

→

Vector Code

**S**ingle **I**nstruction **M**ultiple **D**ata (SIMD)

```
{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?

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{A1,A2}
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```

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

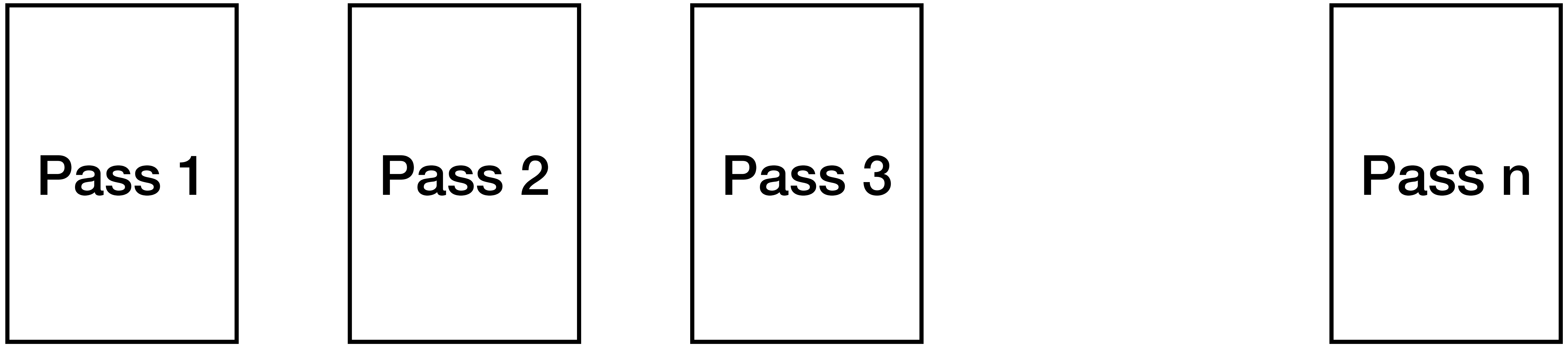
What are **all** vectorization possibilities?

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

# How to make step decisions?

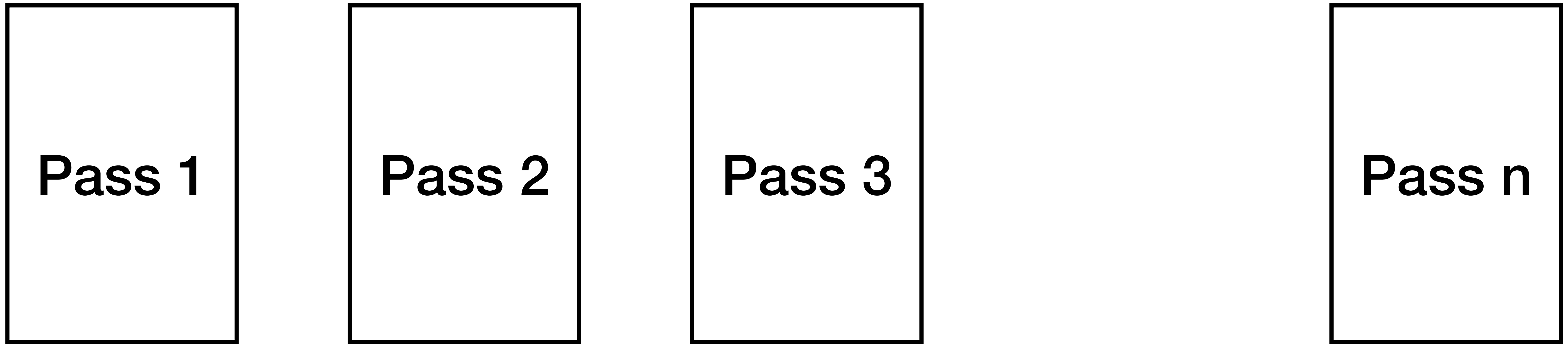
- Enumerate all possible choices and select the most profitable?
- **Intelligent Search**
  - Meta Optimization: improving compiler heuristics with machine learning (PLDI 2003)
- **Learned Optimizations**
  - Compiler Auto-vectorization using Imitation Learning (NeurIPS 2019)
  - NeuroVectorizer: End-to-End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

# Multiple Optimization Passes




How do we compose these passes?

# Multiple Optimization Passes

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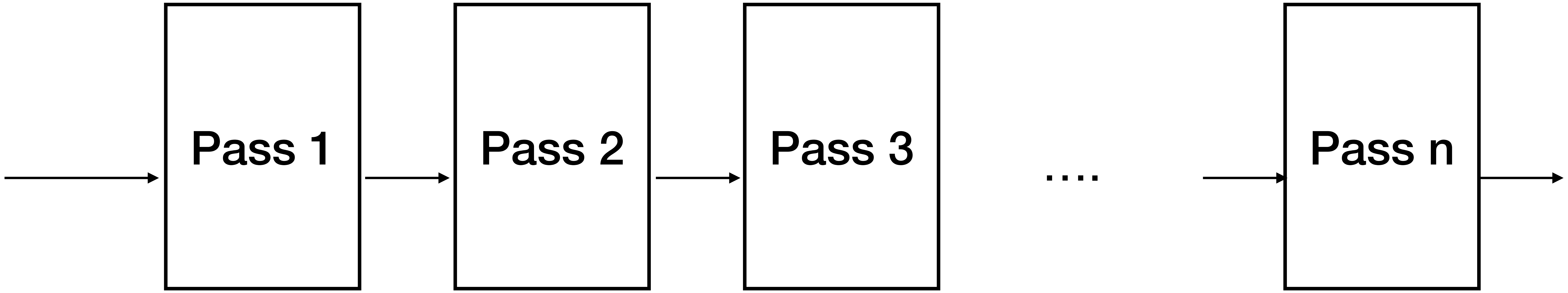
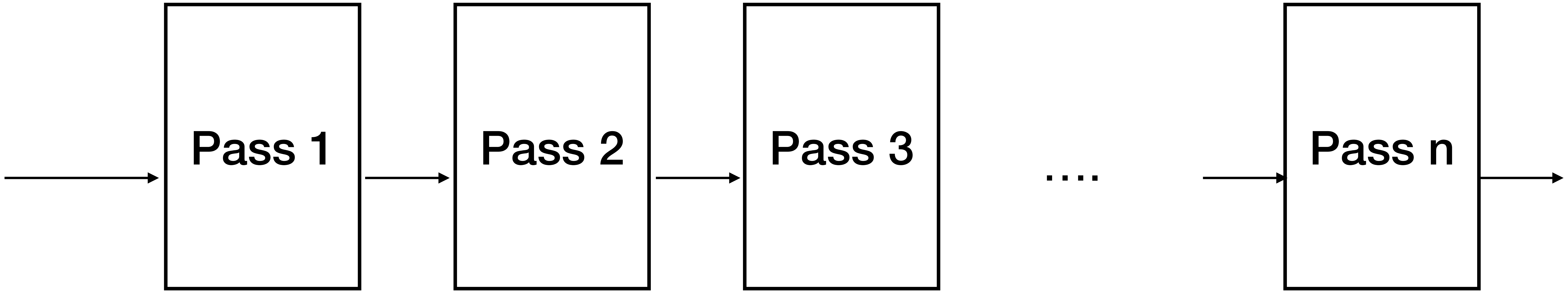



How do we compose these passes? Run them in sequence

# Multiple Optimization Passes

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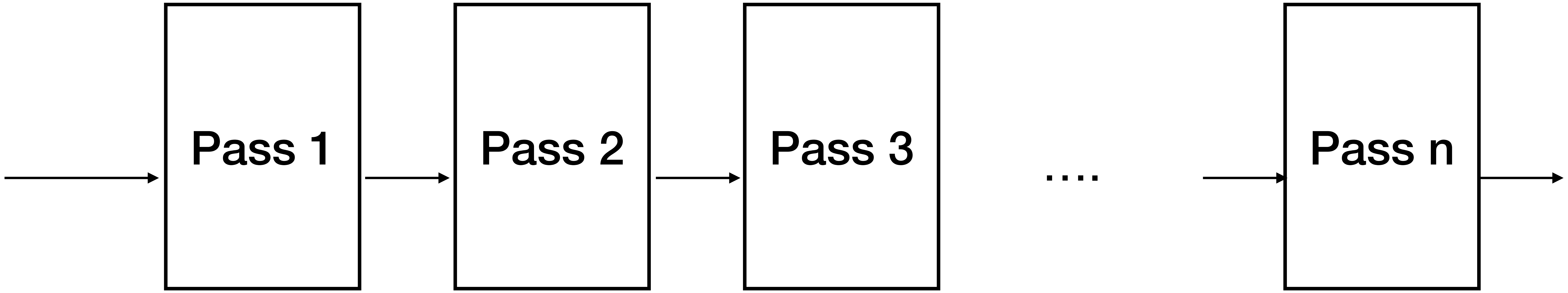
Faces the same challenges at Type II Optimizations:
Now passes are the steps

**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?