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Chapter 1
Introduction to Compilers

授课老师及助教

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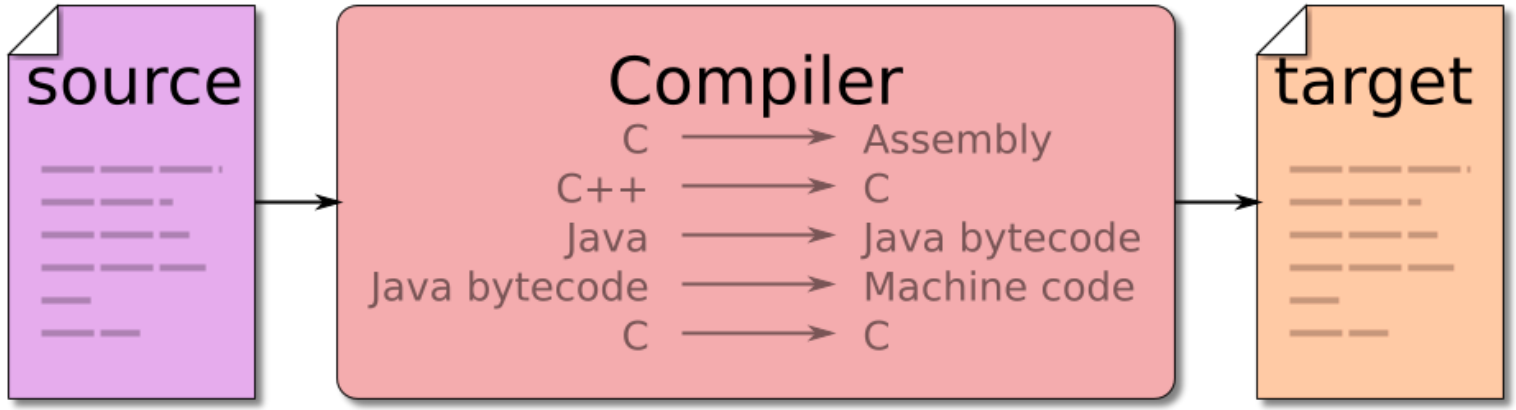
PART I: What is a Compiler?

What is a Compiler?

- A compiler translates source language into target language
  - C/C++/Java/… to x86/Java bytecode/…
- Some compiler may also translate a source language to another
  - C to Rust translation, a hot research topic



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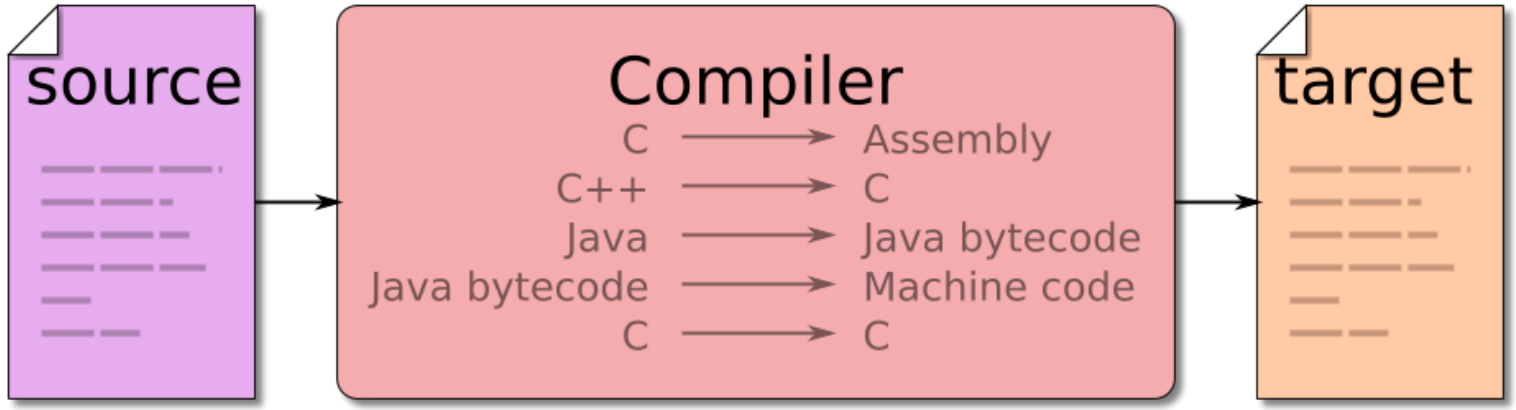
Transpiler



Compiler vs. Interpreter

- What is an interpreter? Any differences?

Compiler vs. Interpreter

- Interpreter does not translate the source to another language, but directly interprets statements in the source language
  - Shell, Javascripts, Python, …

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  - Shell, Javascripts, Python, …
- **Java is special: compiler + interpreter + just-in-time compiler**

Compiler vs. Linker

- What is a linker?

Compiler vs. Linker

- Linking multiple compilation units into a single file, which could be an executable, a library, …

How does a Compiler/Linker Work?

- Using gcc as the compiler to compile programs in C

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```
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Compile

```
gcc  -c  file1.c  -o  file1.o
```

```
gcc  -c  file2.c  -o  file2.o
```

```
gcc  -c  file3.c  -o  file3.o
```

How does a Compiler/Linker Work?

- Using gcc as the compiler to compile programs in C

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gcc  file1.c  file2.c  file3.c  -o  executable.exe
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Compile

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gcc  -c  file1.c  -o  file1.o
```

```
gcc  -c  file2.c  -o  file2.o
```

```
gcc  -c  file3.c  -o  file3.o
```

Link

```
gcc  *.o  -o  executable.exe
```

For example:

- file1.c declares and uses foo()
- file2.c defines foo()

How does a Compiler/Linker Work?

- Using gcc as the compiler to compile programs in C

```
gcc   file1.c   file2.c   file3.c   -o   executable.exe
```

Compile

```
gcc -c -O1 file1.c -o file1.o
```

```
gcc -c -O1 file2.c -o file2.o
```

```
gcc -c -O1 file3.c -o file3.o
```

Link

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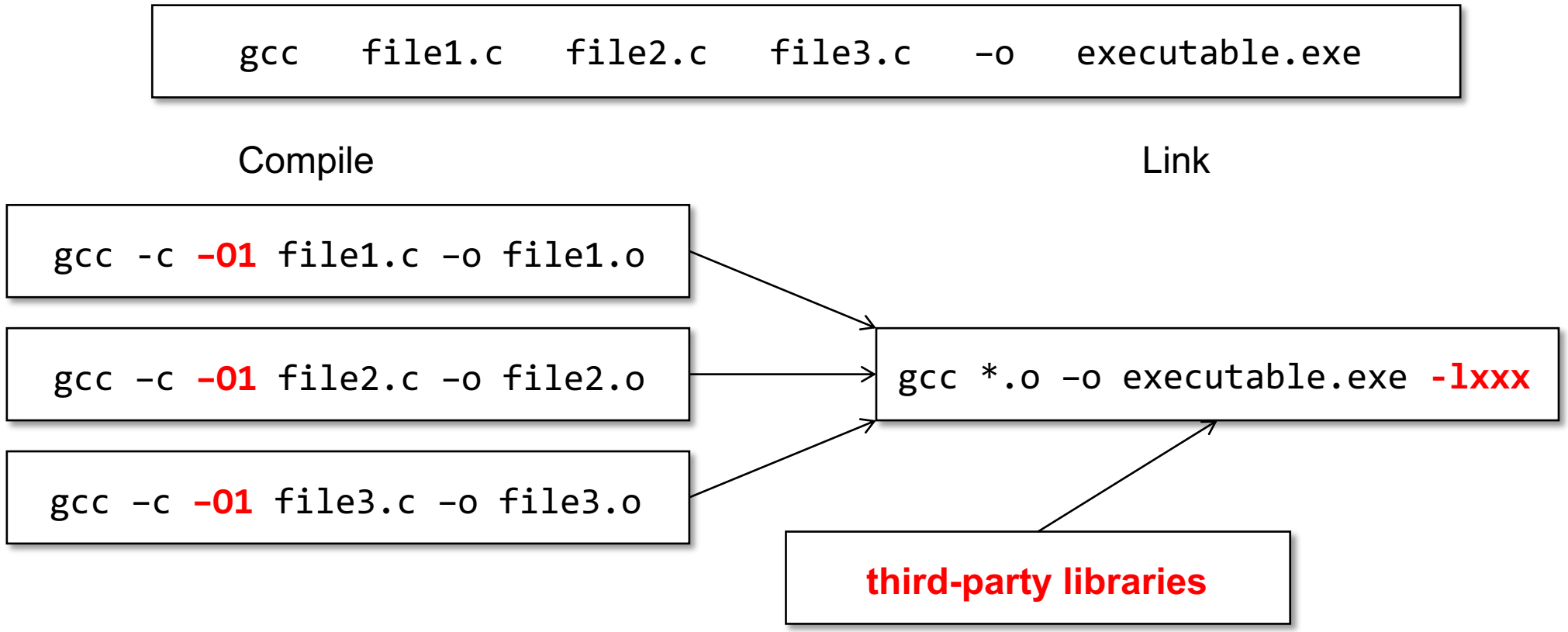

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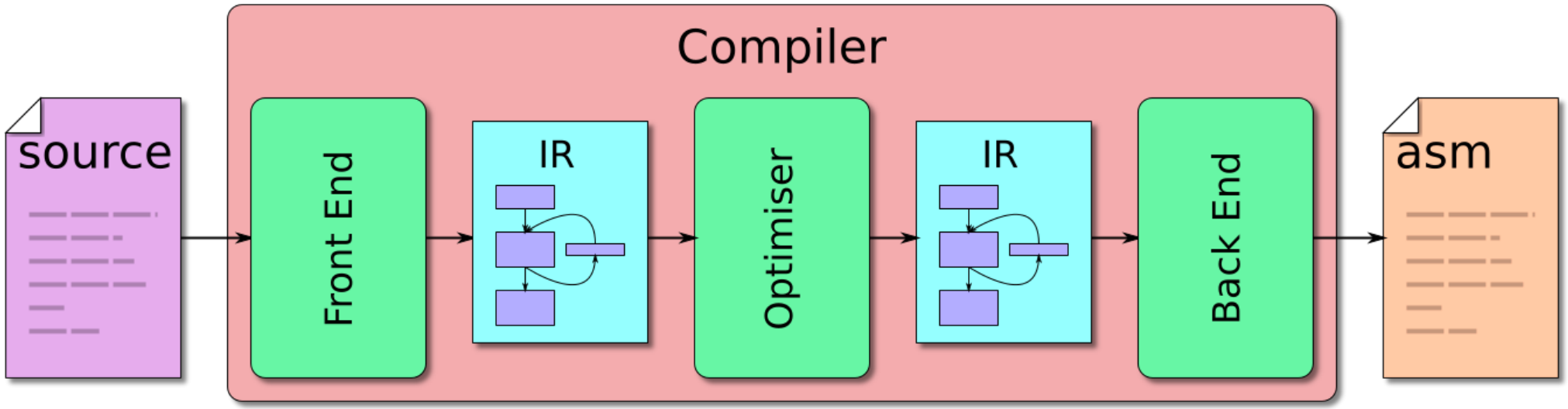

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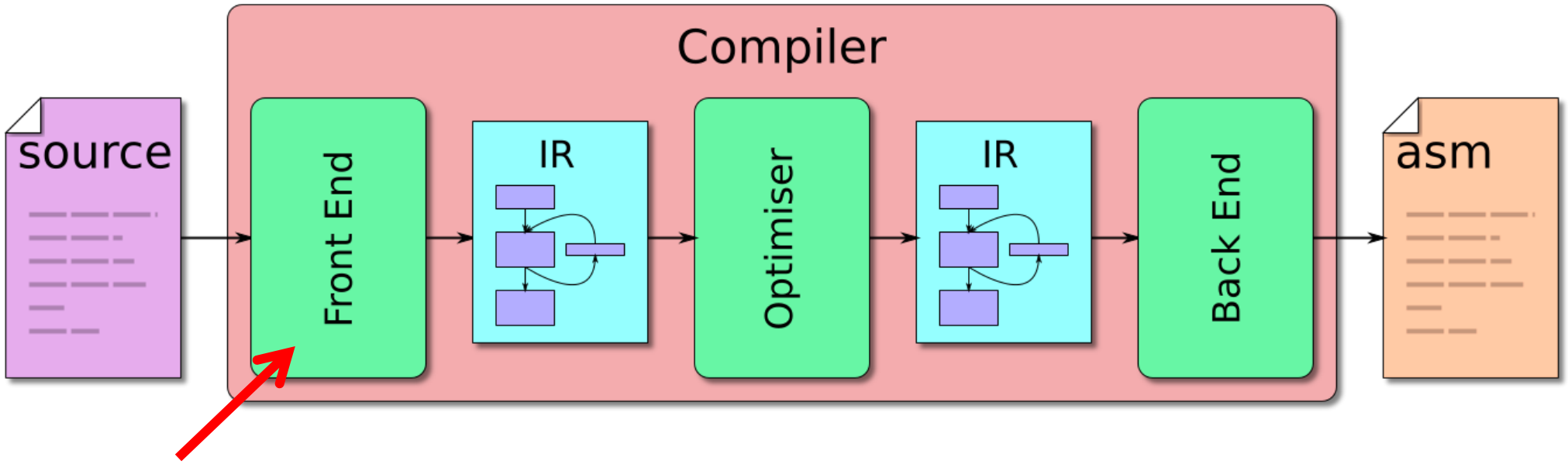
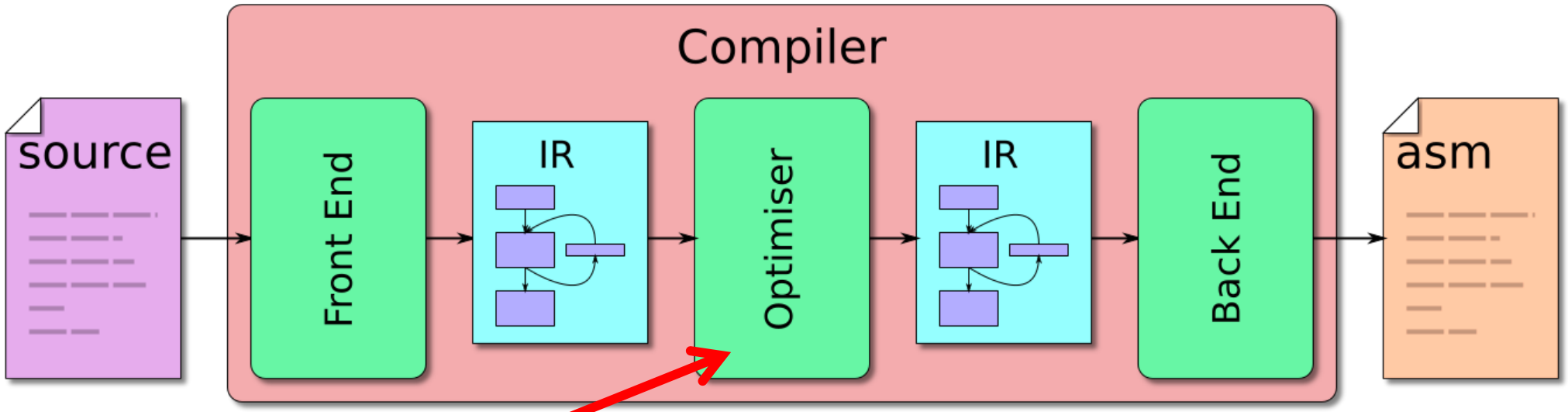


- **Front End**: read text in the source file, translate into IR

How does a Compiler/Linker Work?



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- **Middle End**: machine-independent optimization, IR → IR

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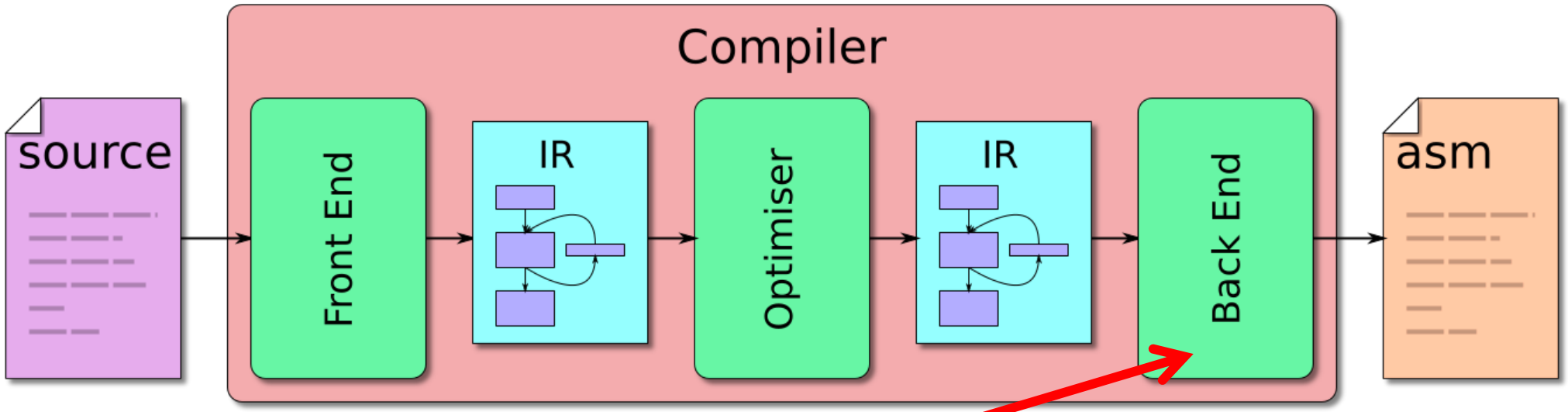
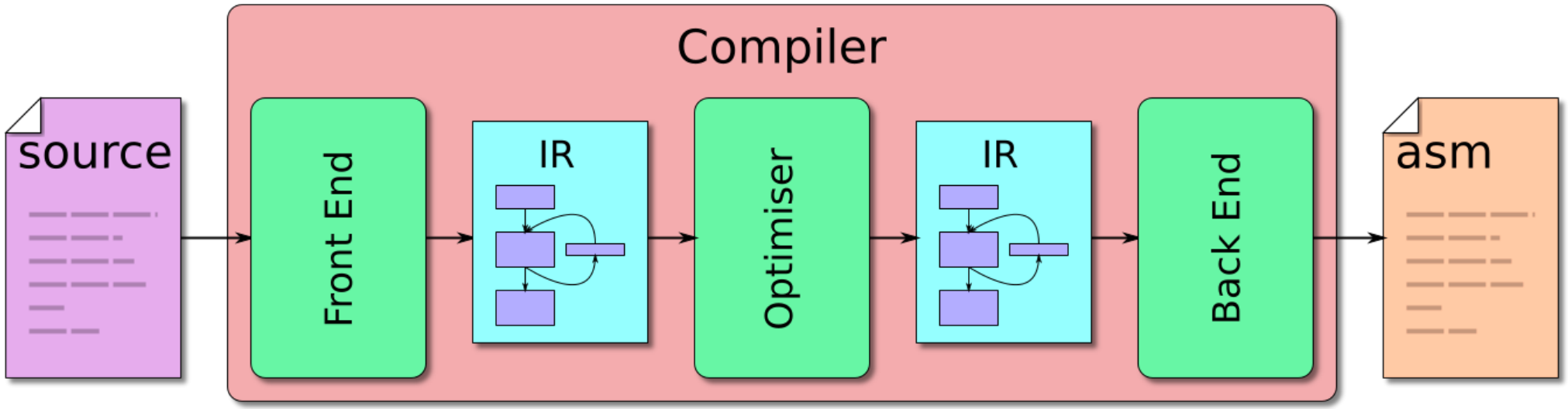


- **Front End**: read text in the source file, translate into IR
- **Middle End**: machine-independent optimization, IR → IR
- **Back End**: machine-dependent optimization and target generation

Breaking into Small Steps



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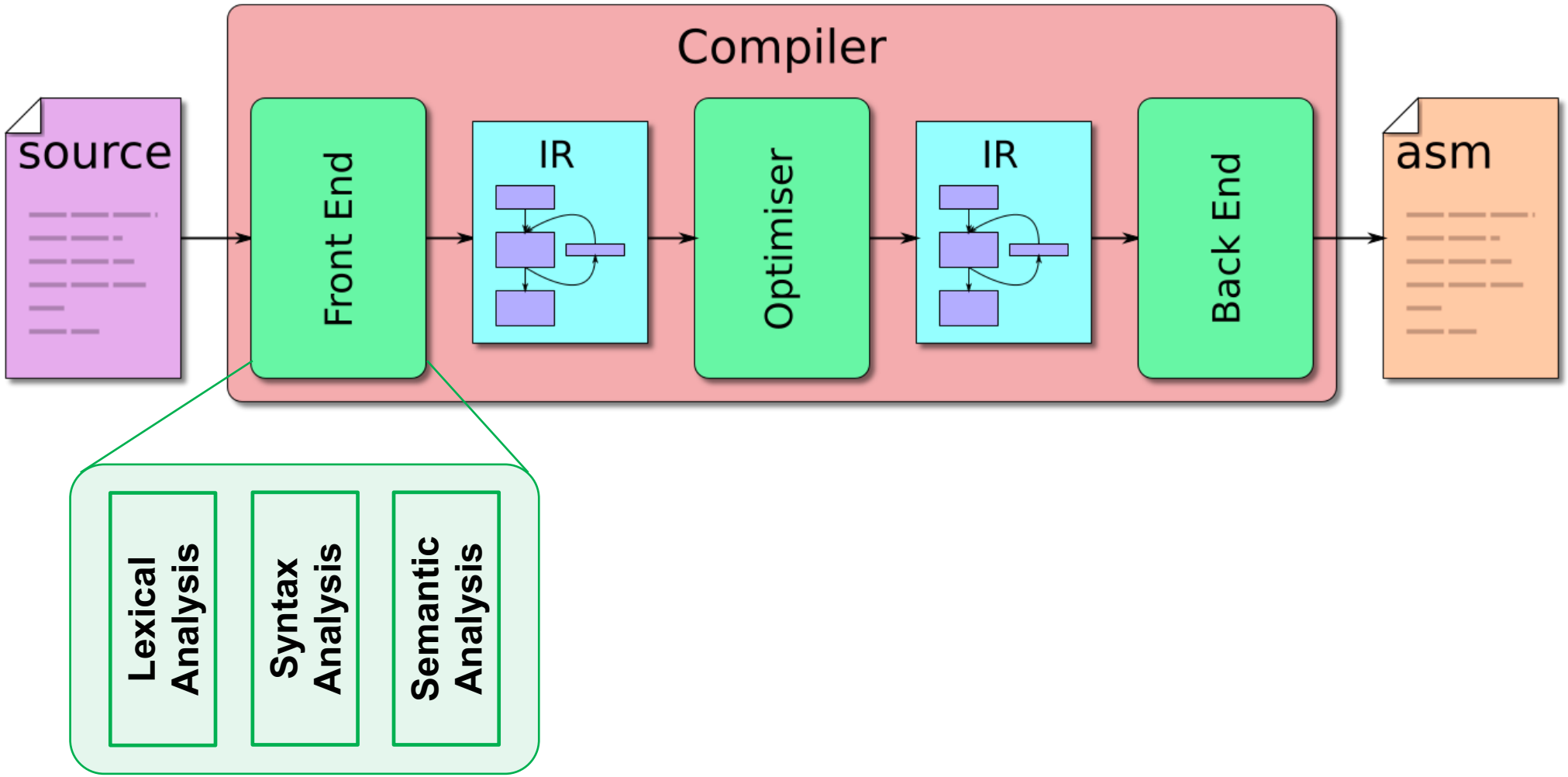

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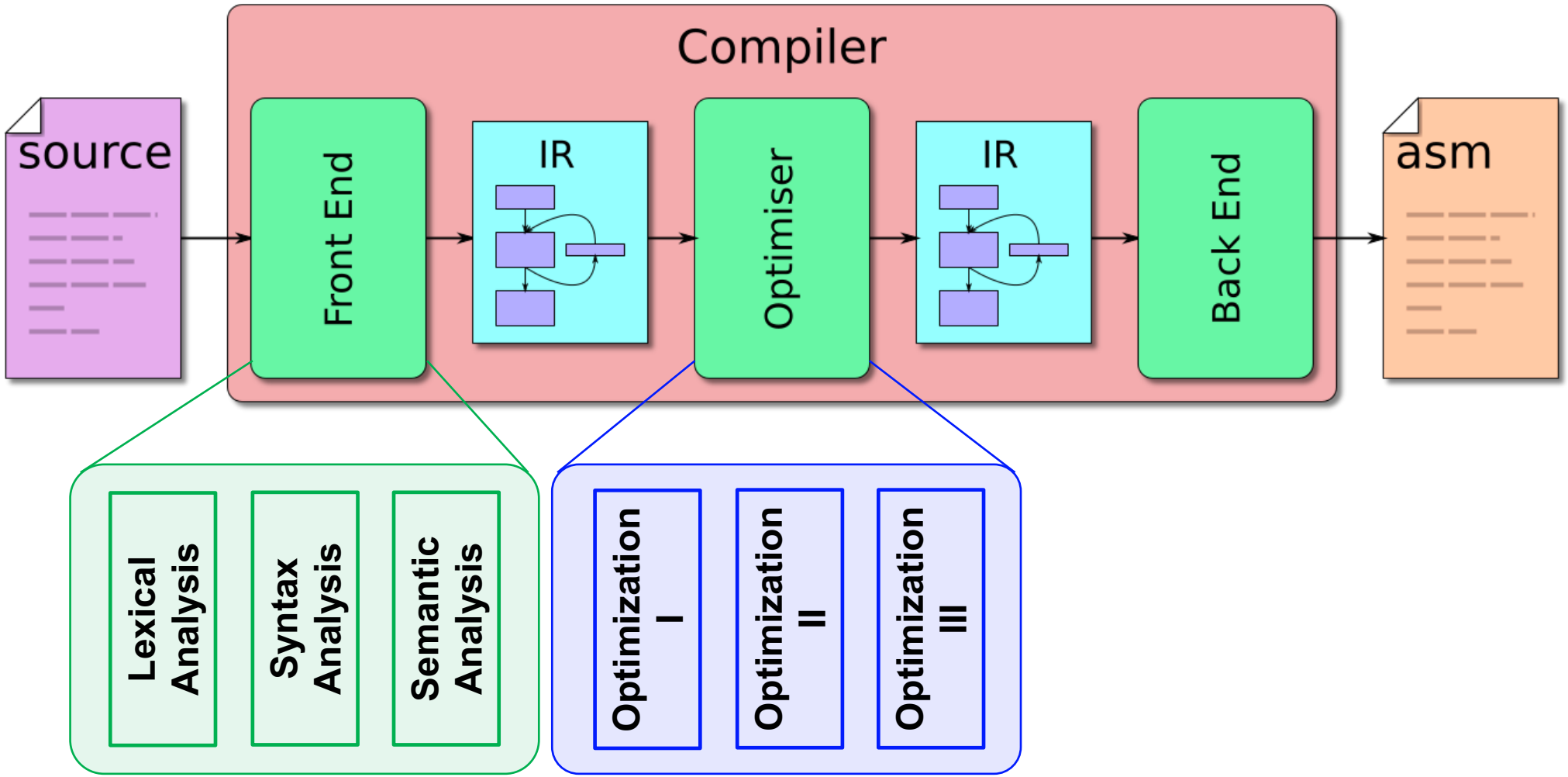

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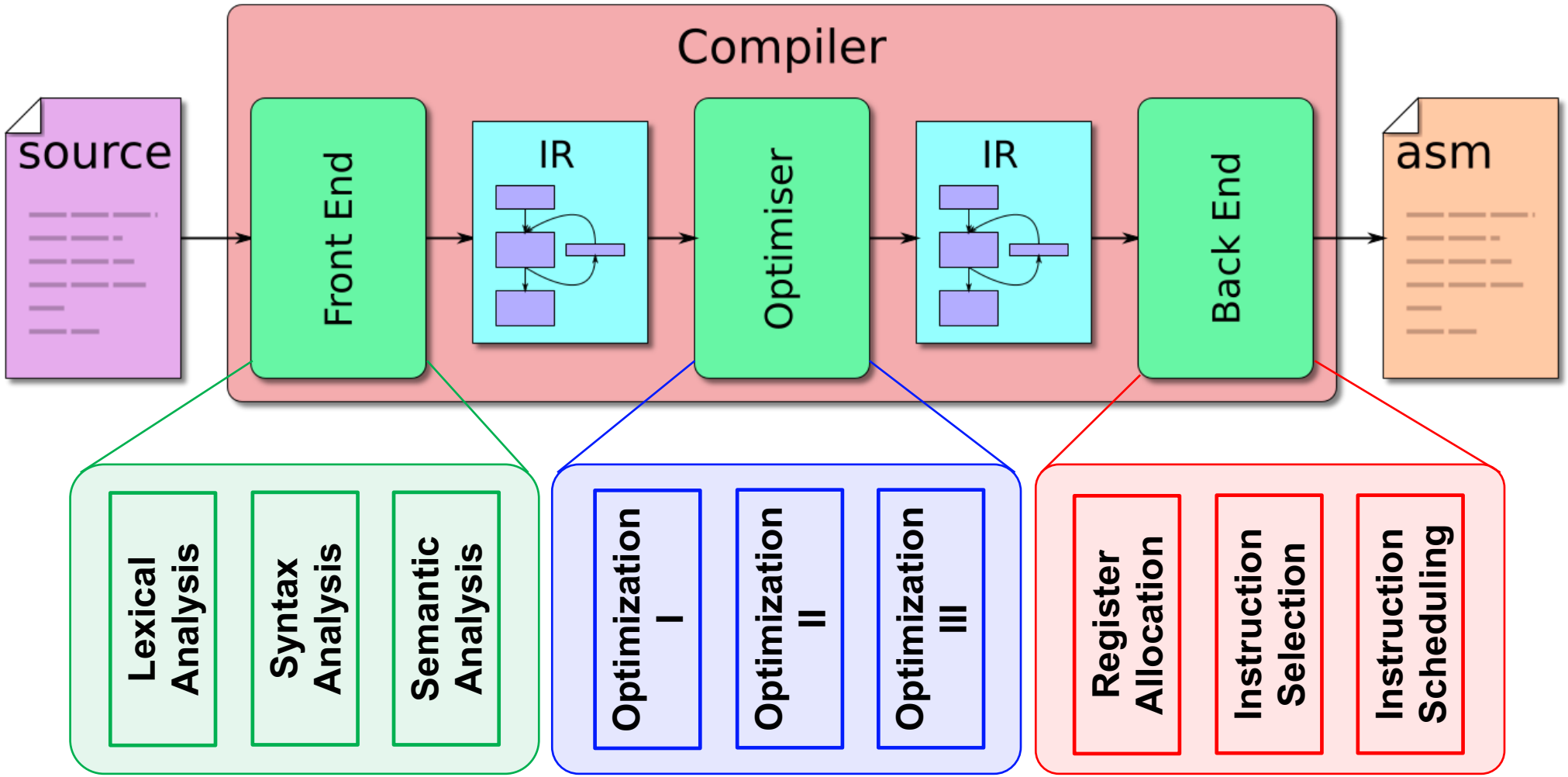
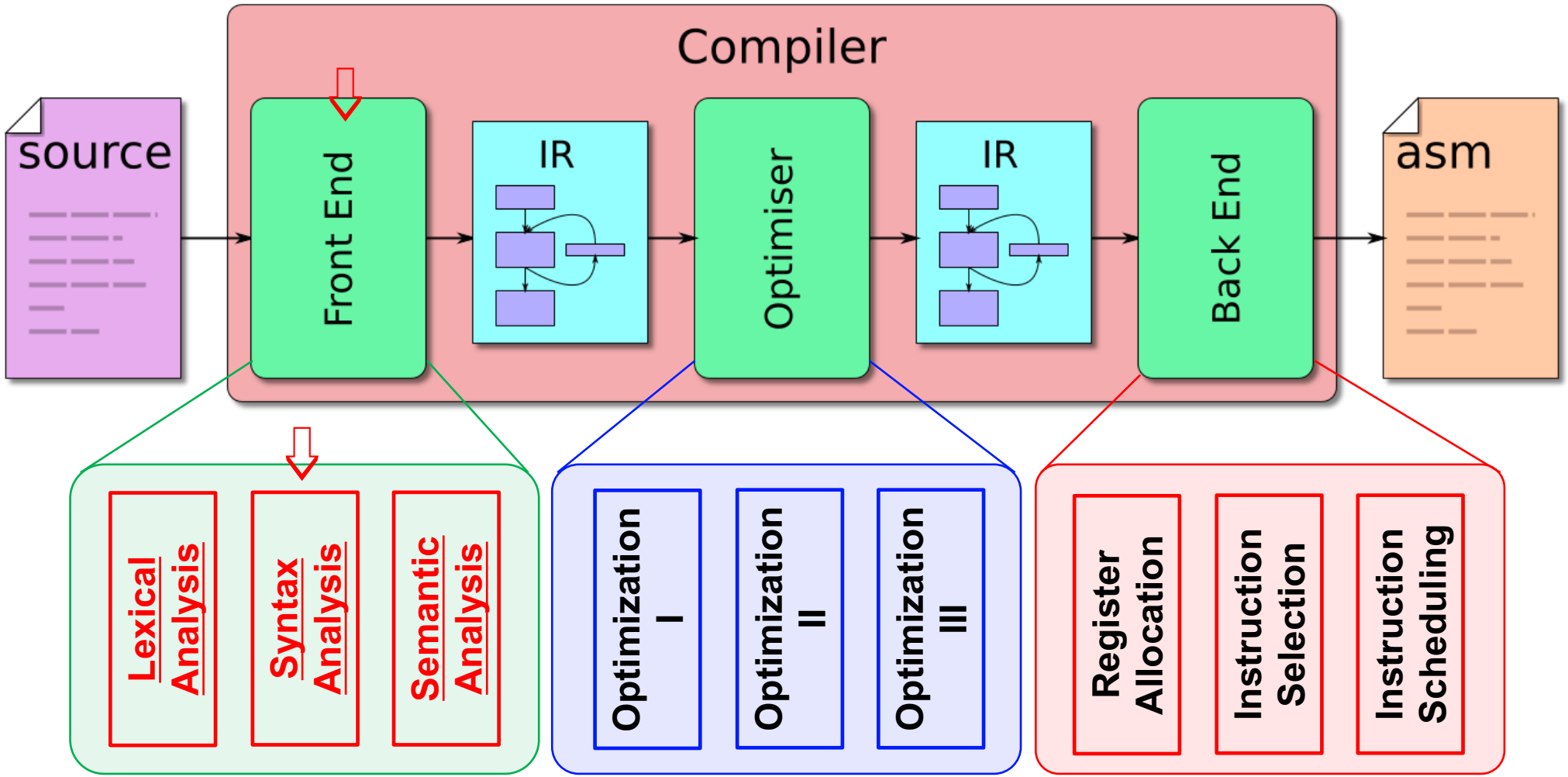


Front End


Compiler
source
Front End
IR
Optimiser
IR
Back End
asm
Lexical Analysis
Syntax Analysis
Semantic Analysis
Optimization I
Optimization II
Optimization III
Register Allocation
Instruction Selection
Instruction Scheduling

Front End

- Lexical Analysis → Syntax Analysis → Semantic Analysis

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T h i s l i n e i s a l o n g s e n t e n c e

Front End

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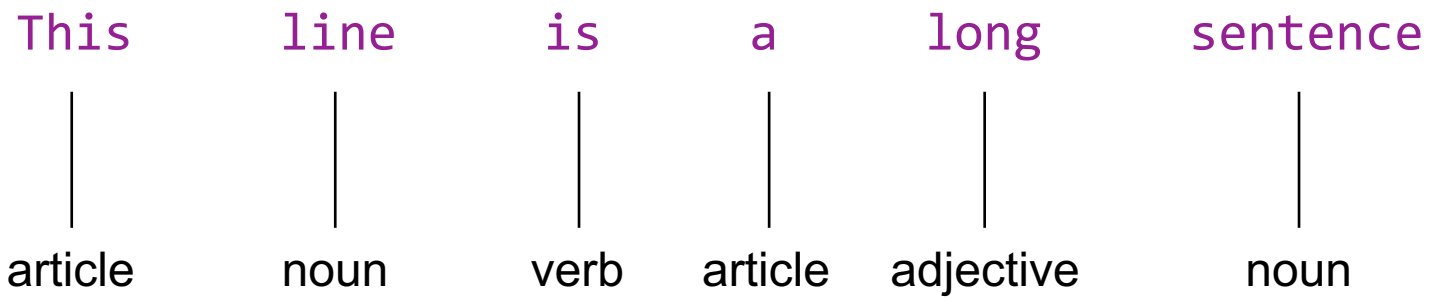

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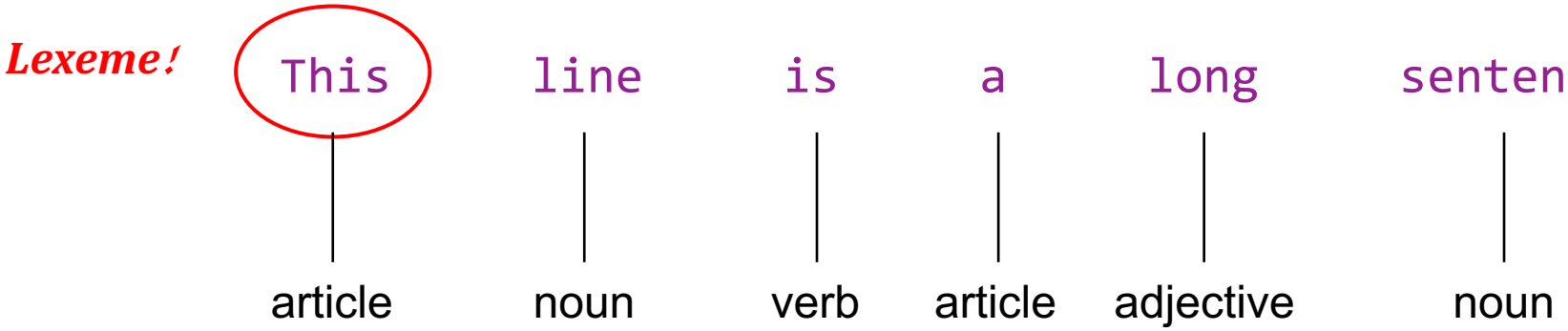

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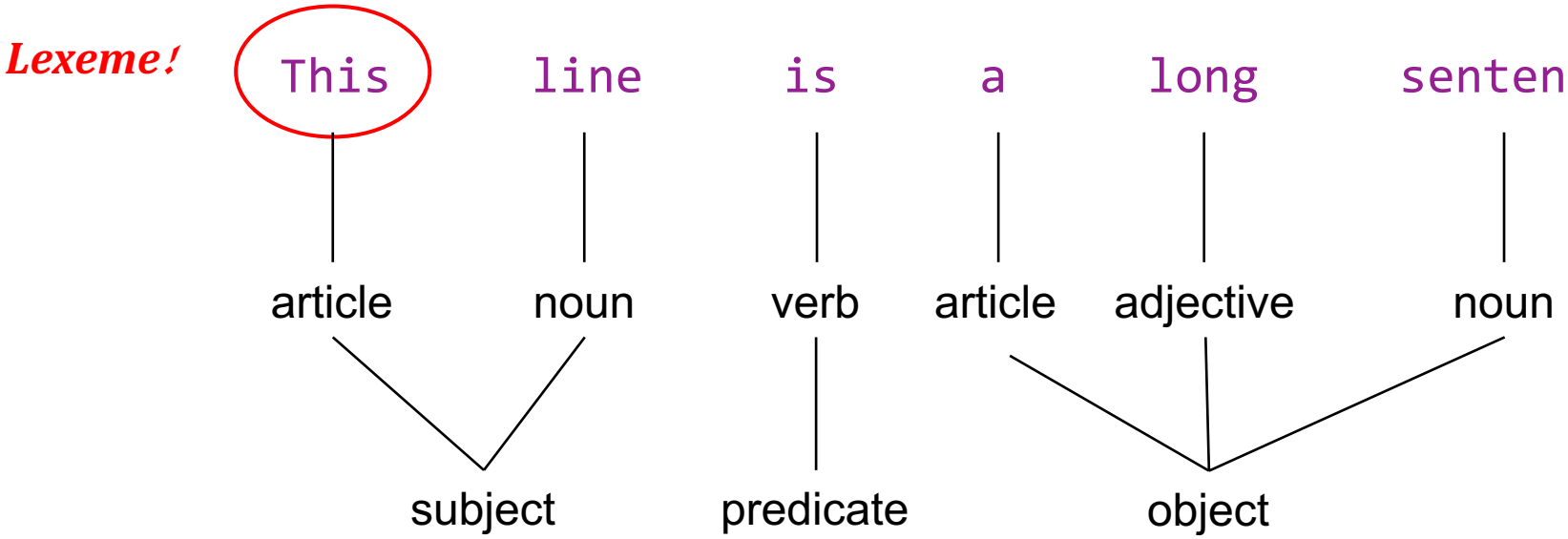

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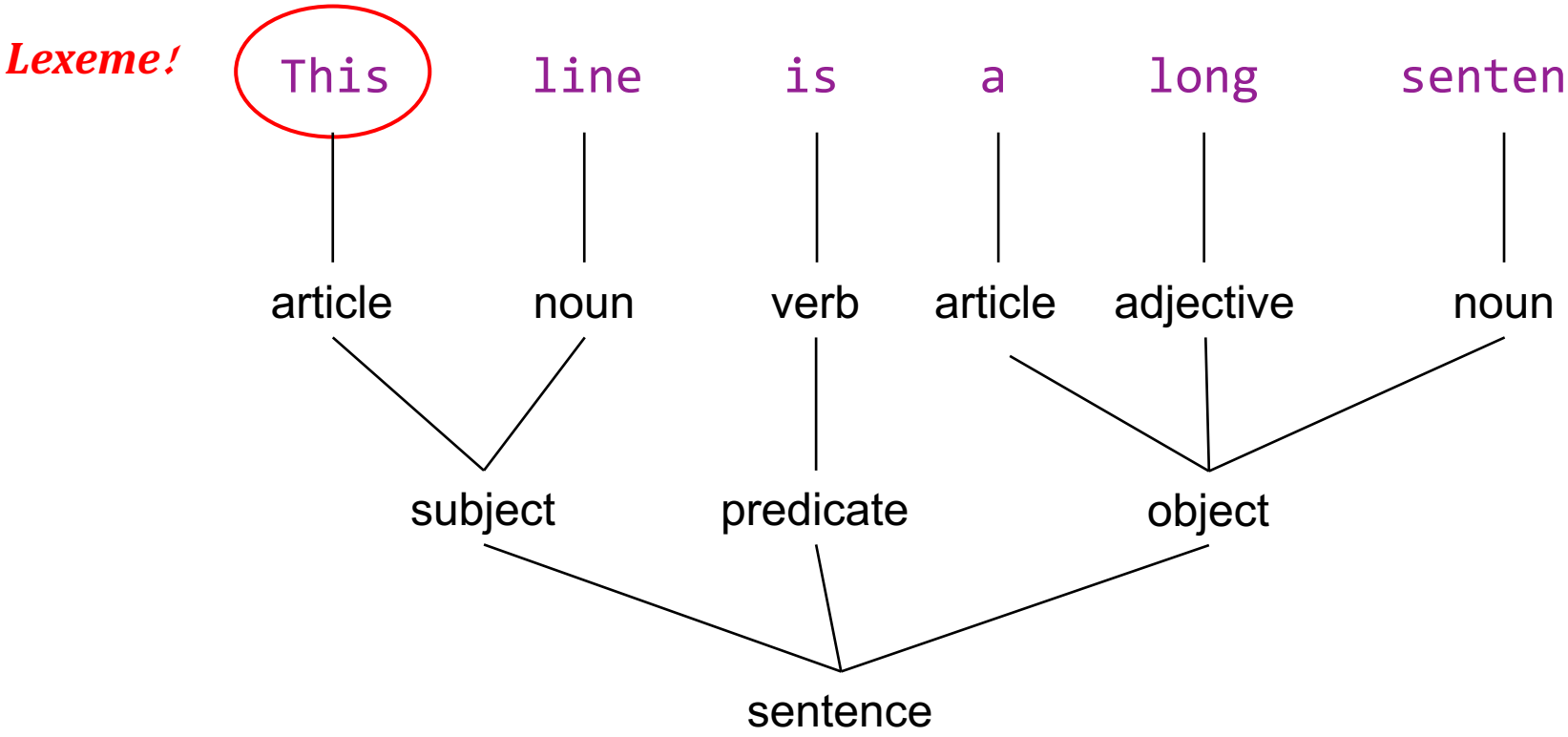

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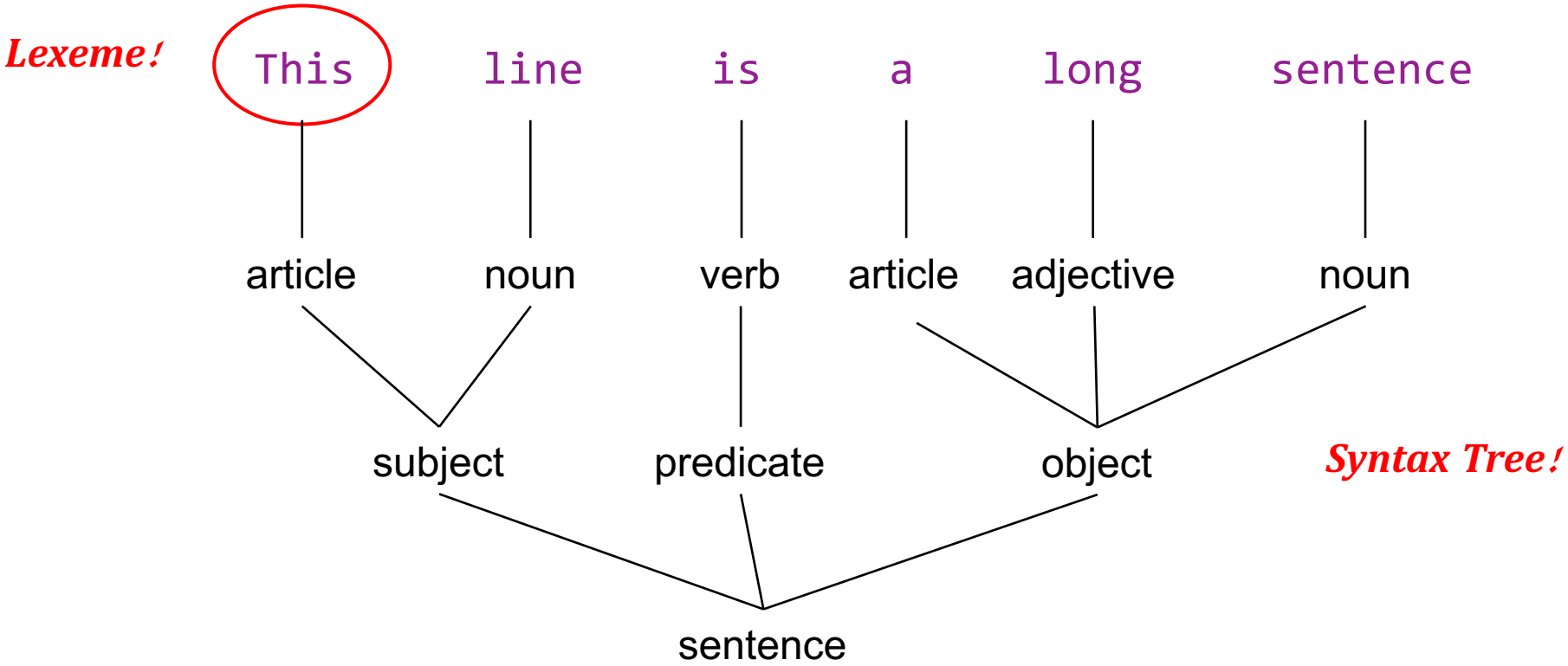

Front End: Lexical Analysis

- Find **lexemes** according to **patterns**, and create **tokens**
  - Lexeme – a character string
  - Pattern – regular expression (lexical errors if no patterns matched)
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```
p o s i t i o n  =  i n i t i a l  +  r a t e  *  6 0
```

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```
position  =  initial  +  rate  *  60
```

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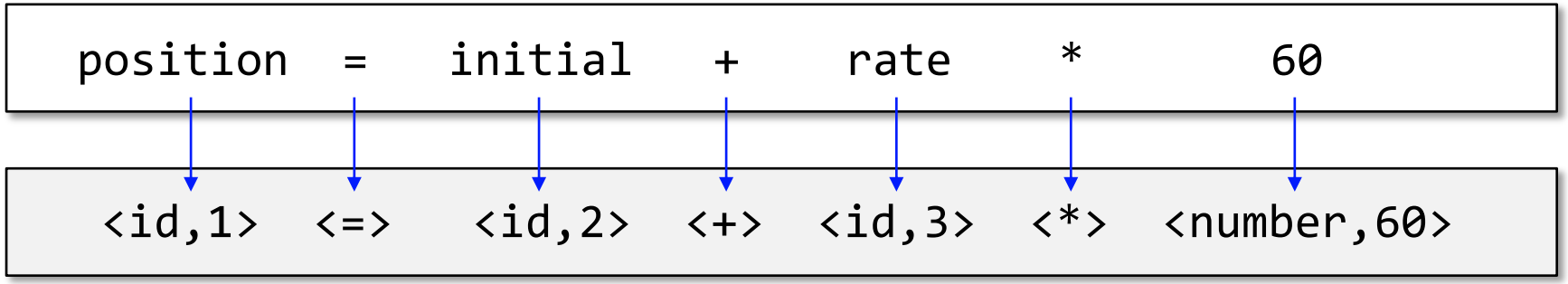

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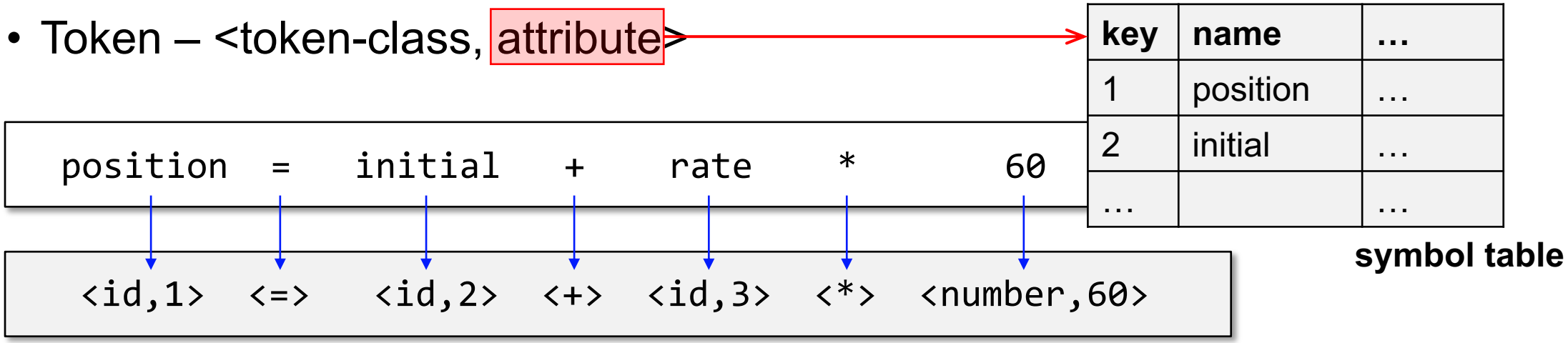

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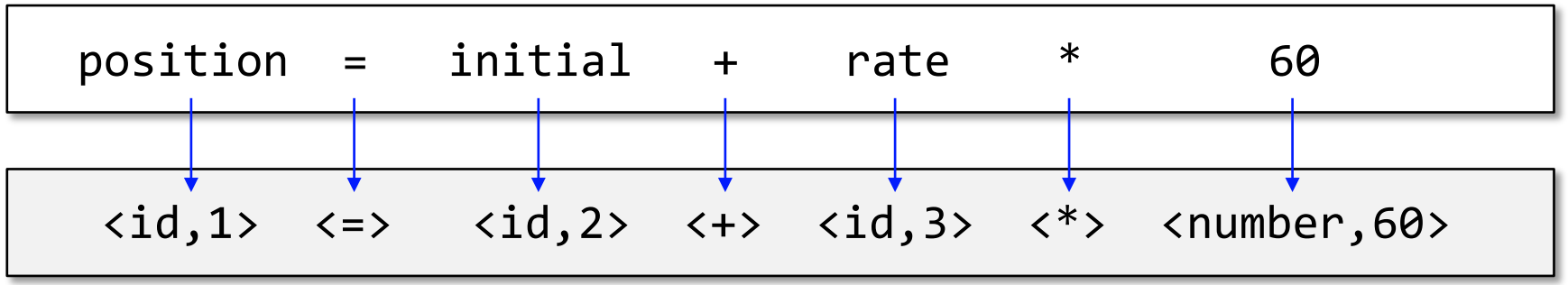

symbol table

key	name	…
1	position	…
2	initial	…
3	rate	…
…	…	…

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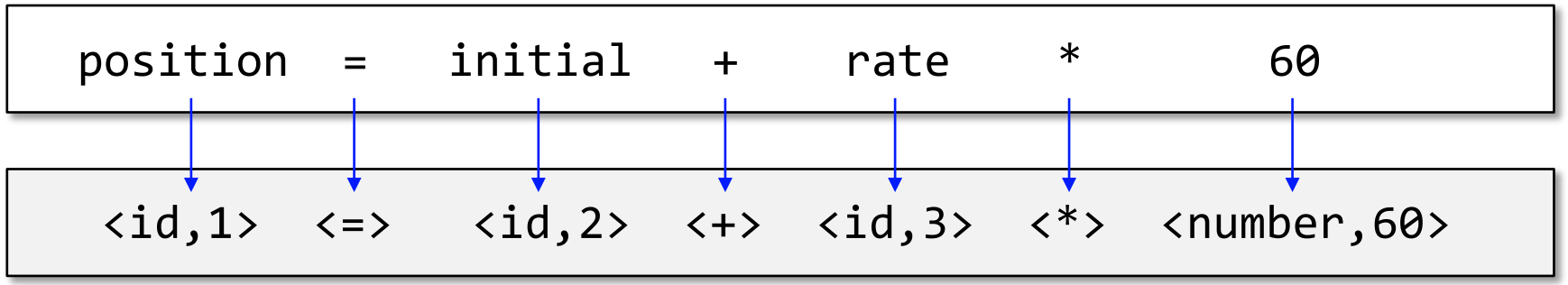

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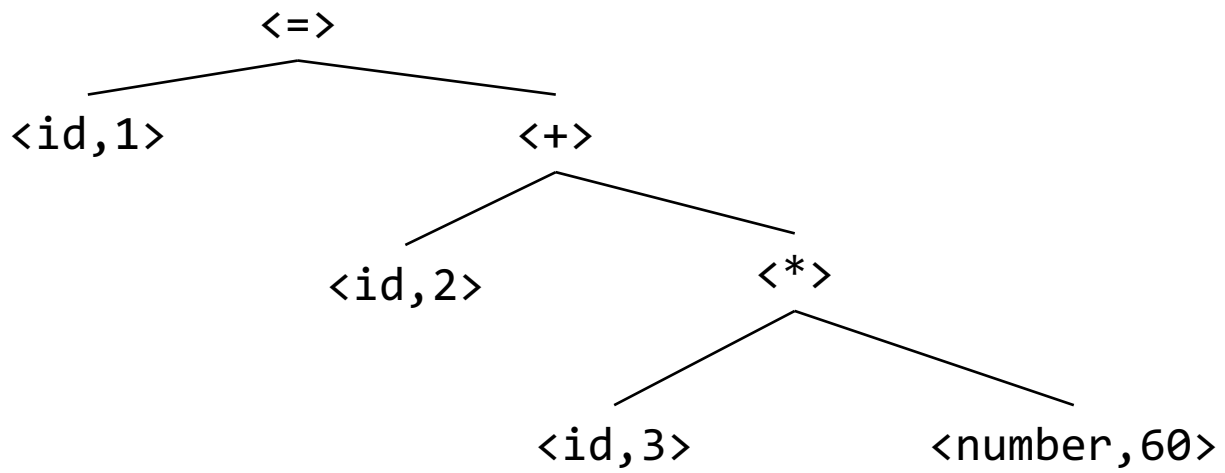

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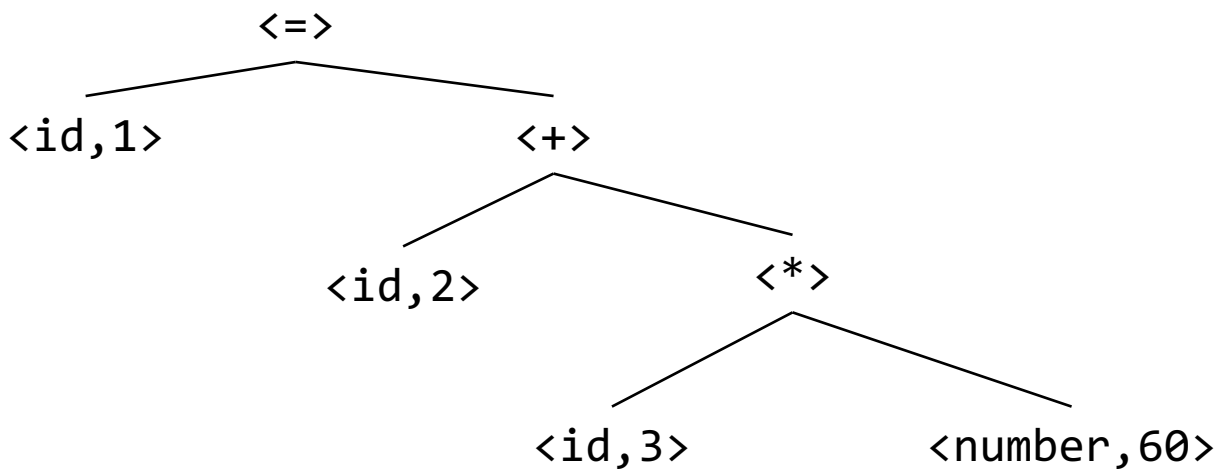

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1	position	float
2	initial	double
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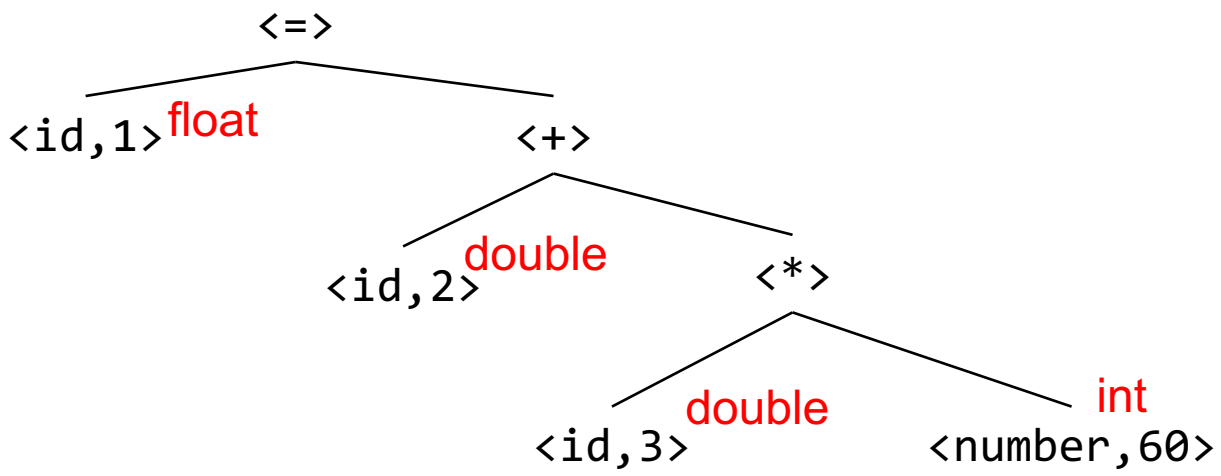

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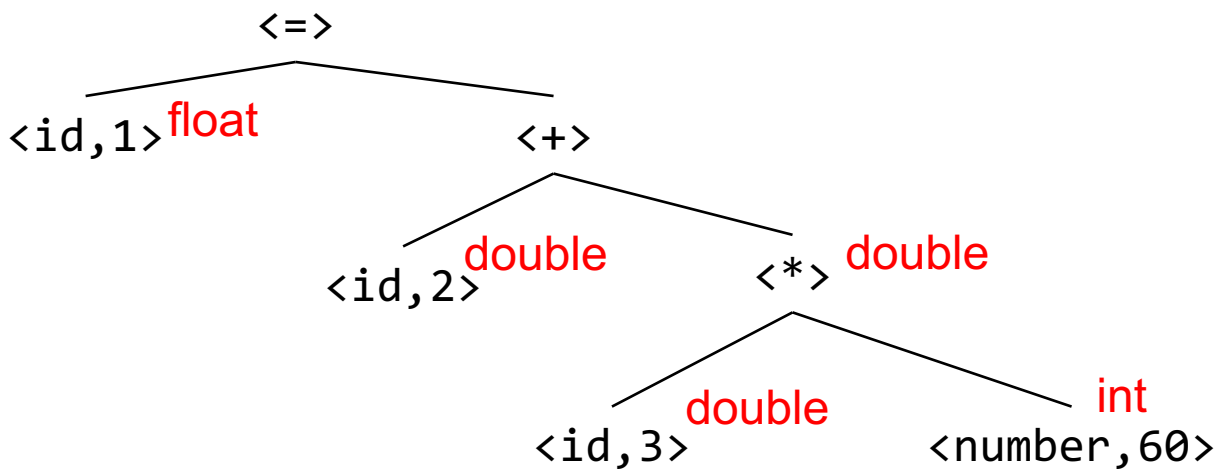

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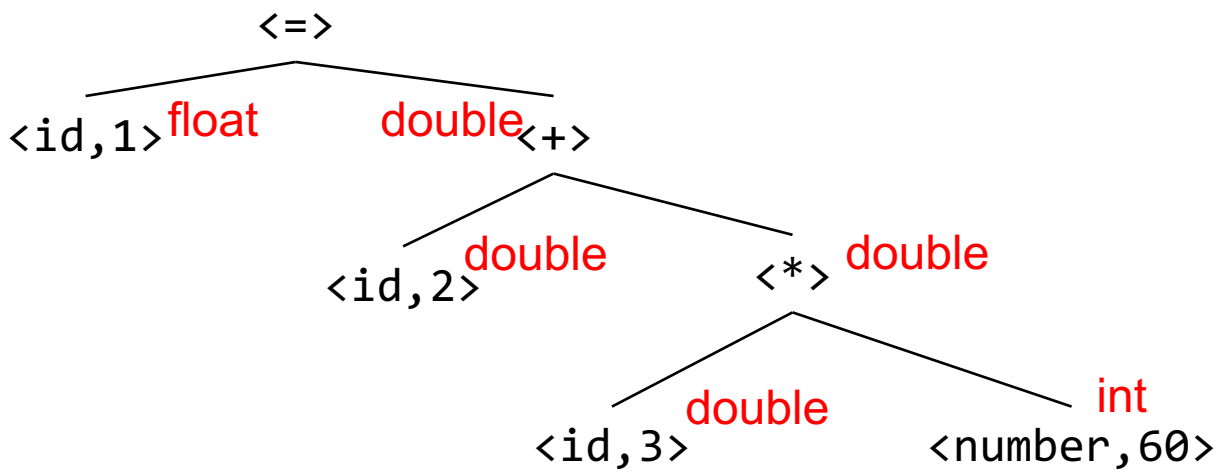

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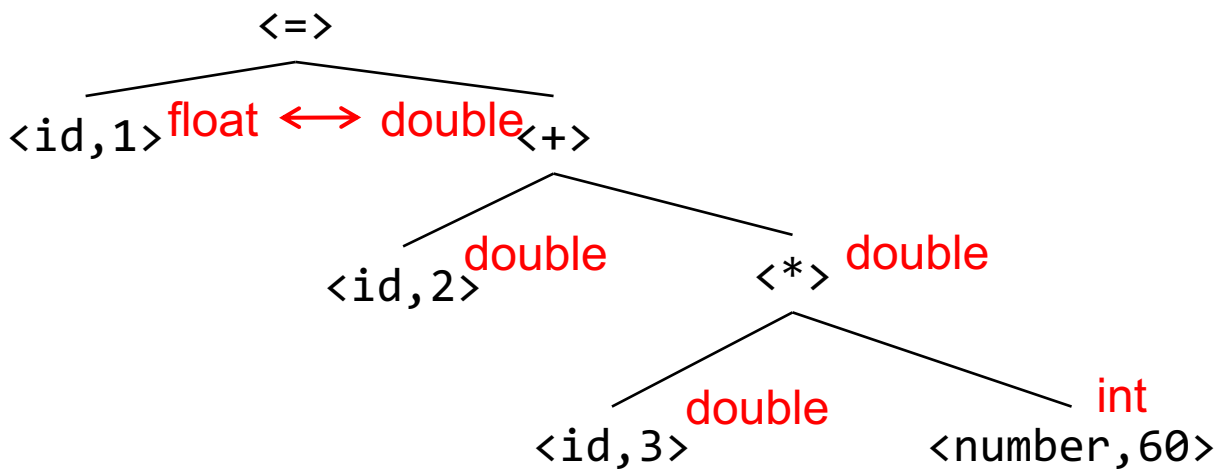

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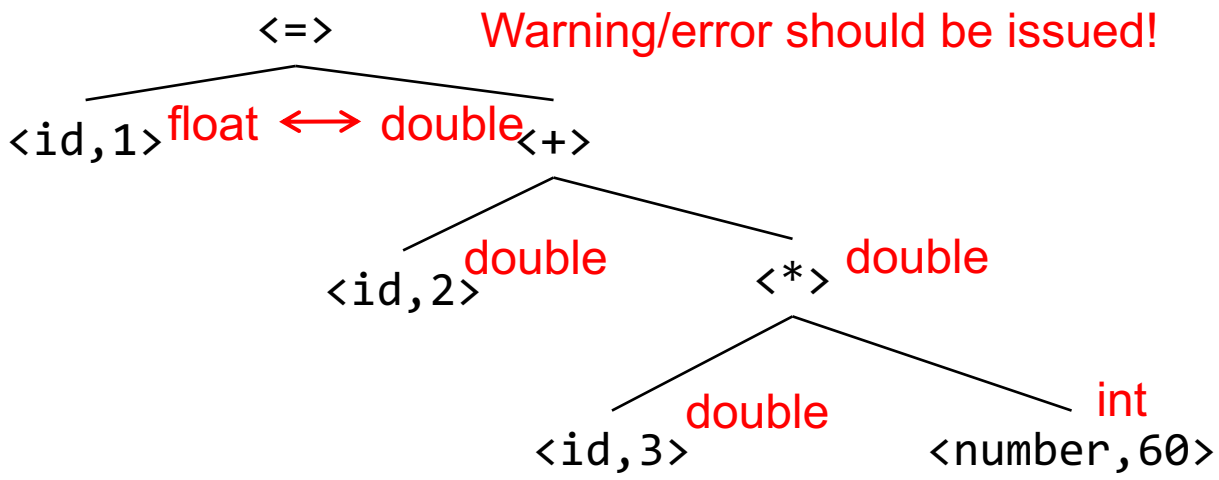

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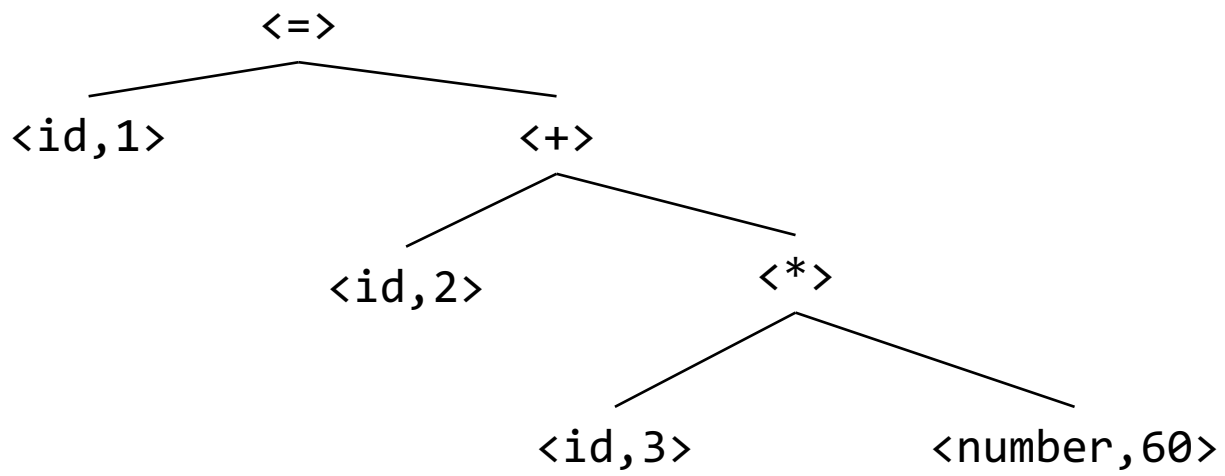

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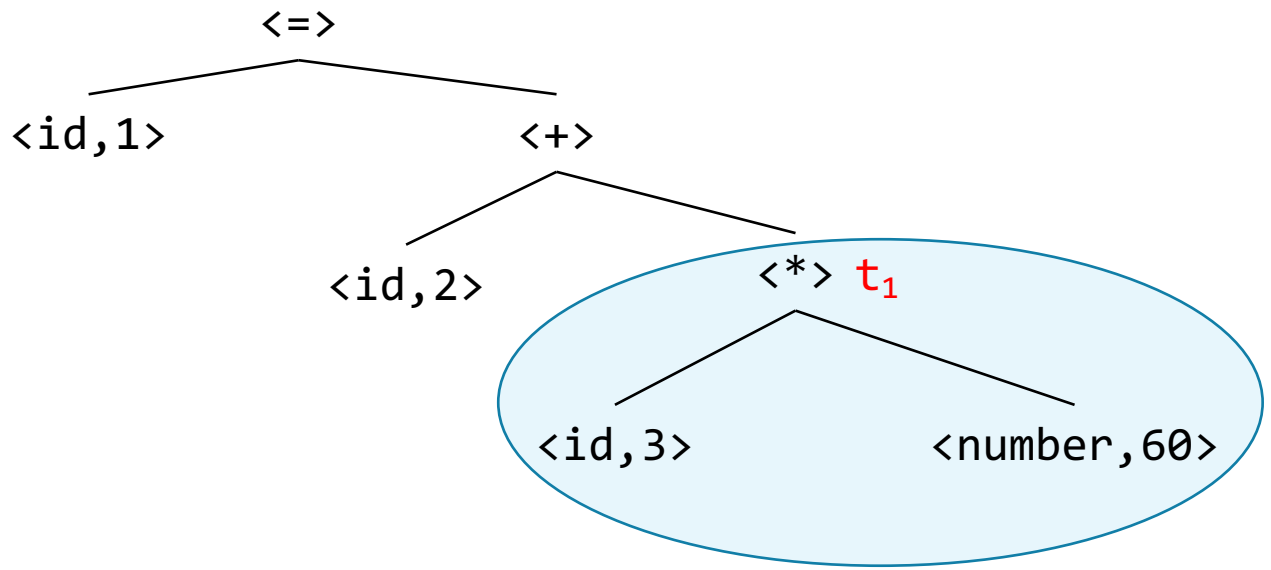

$t_1 = id_3 * 60$

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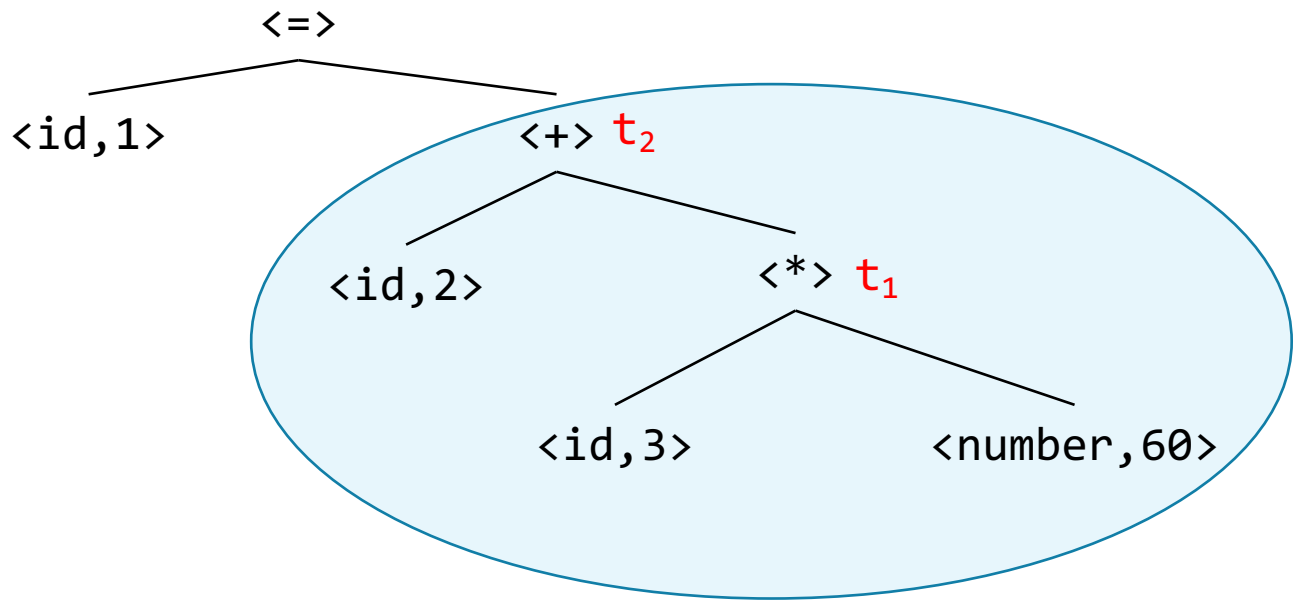

$t_1 = id_3 * 60$

$t_2 = id_2 + t_1$

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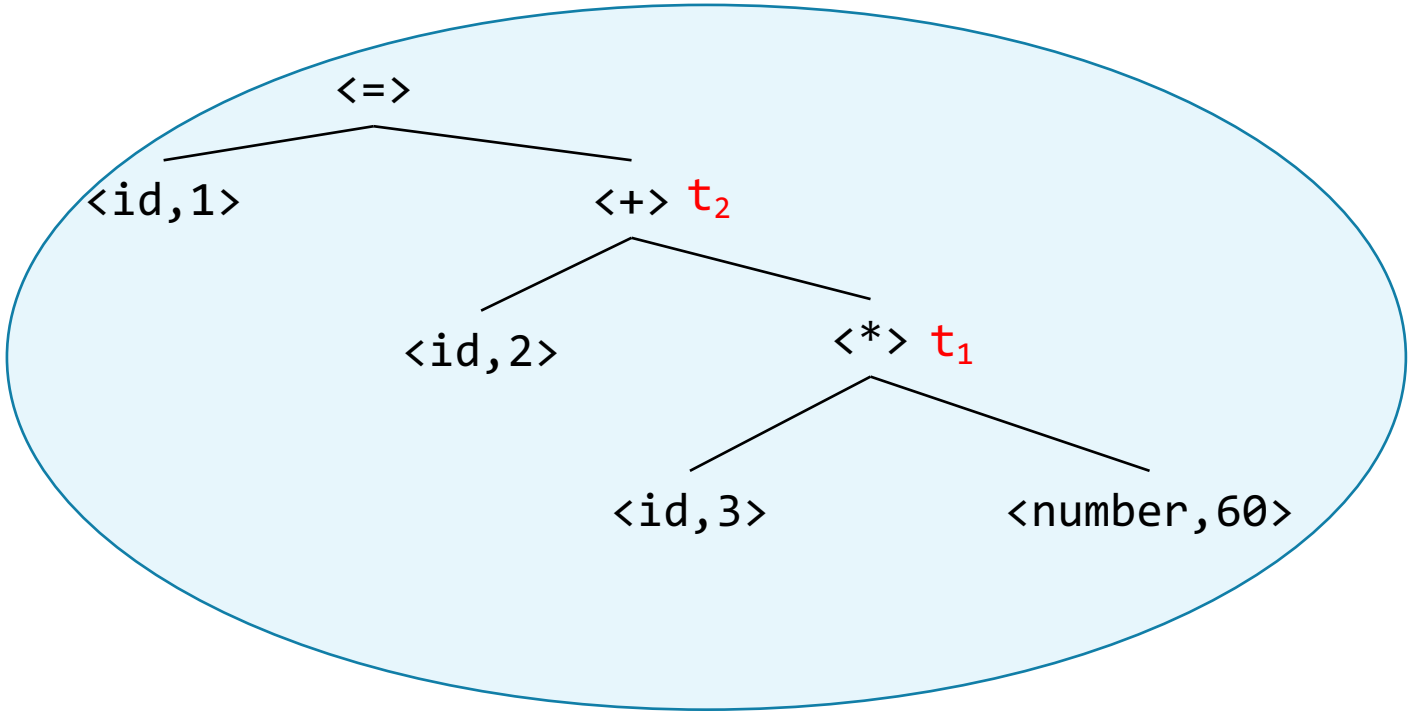

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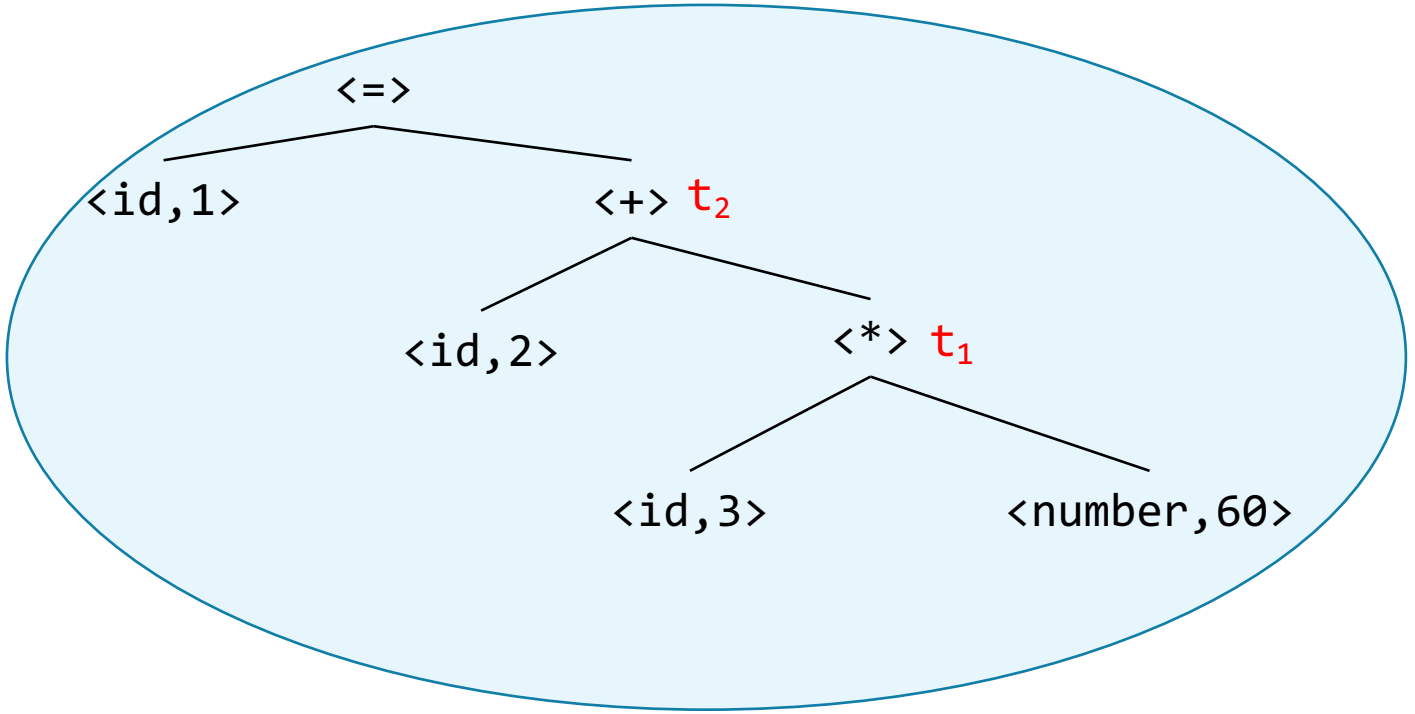

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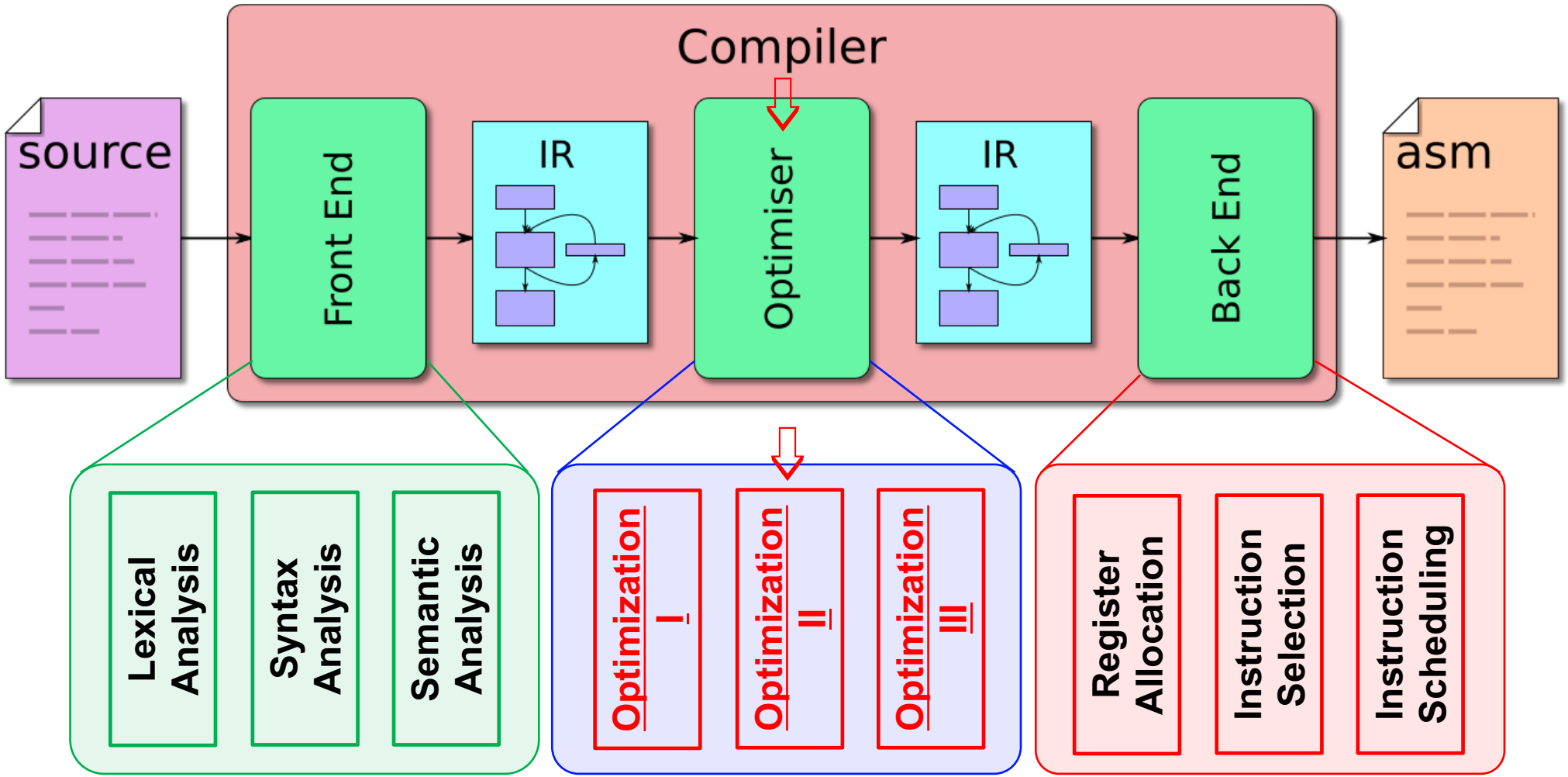
Three-address code

Middle End


Compiler
source
Front End
IR
Optimiser
IR
Back End
asm
Lexical Analysis
Syntax Analysis
Semantic Analysis
Optimization I
Optimization II
Optimization III
Register Allocation
Instruction Selection
Instruction Scheduling

Middle End: Optimizations

- Machine-independent optimizations, working on IR
  - **vs. source code**: IR provides standard form, easier to process
  - **vs. machine code**: IR provides machine-independent abstraction with source information (e.g., types via the symbol table)

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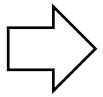
  - **vs. machine code**: IR provides machine-independent abstraction with source information (e.g., types via the symbol table)

```
t1  = id3  *  60
t2  = id2  +  t1
id1 = t2
```

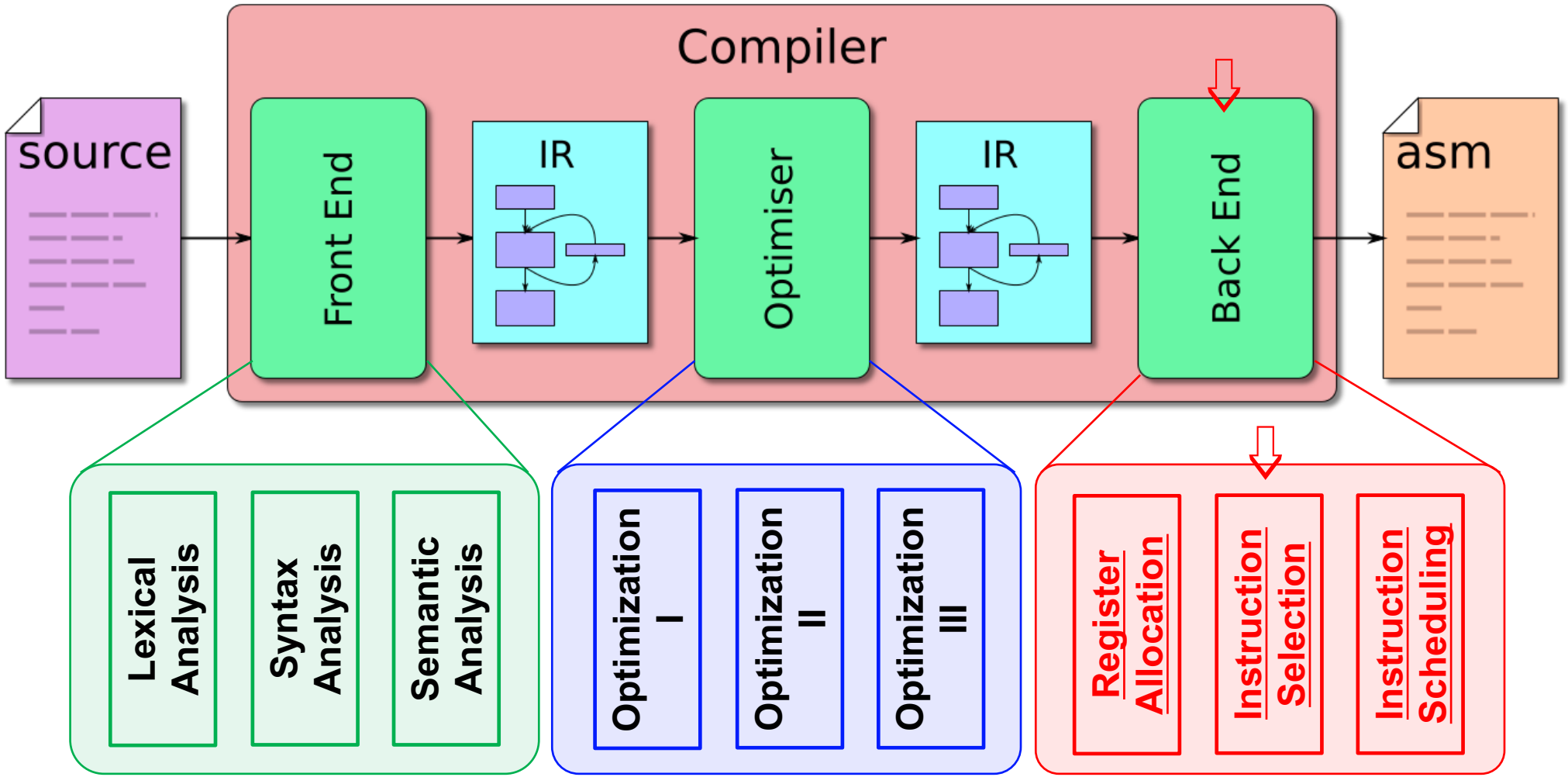
Three-address code



```
t1  = id3  *  60
id1 = id2  +  t1
```

Optimized code

Breaking into Small Steps



Back End: Instruction Selection

- Translate IR to machine code
- Perform machine-dependent optimization

Back End: Instruction Selection

- Translate IR to machine code
- Perform machine-dependent optimization

```
LD   R0, a              // R0 = a
Add  R0, R0, #1         // R0 = R0 + 1
ST   a,  R0             // a = R0
```

Possible machine code for a = a + 1

Back End: Instruction Selection

- Translate IR to machine code
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LD   R0, a              // R0 = a
Add  R0, R0, #1         // R0 = R0 + 1
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```

Possible machine code for a = a + 1

```
INC a          // a = a + 1
```

More compact machine code

Back End: Register Allocation

- Accessing registers is faster than accessing memory

Back End: Register Allocation

- Accessing registers is faster than accessing memory
- **The number of registers is limited**

Back End: Register Allocation

- Accessing registers is faster than accessing memory
- The number of registers is limited
- **Allocating reasonable # registers for machine code generation**

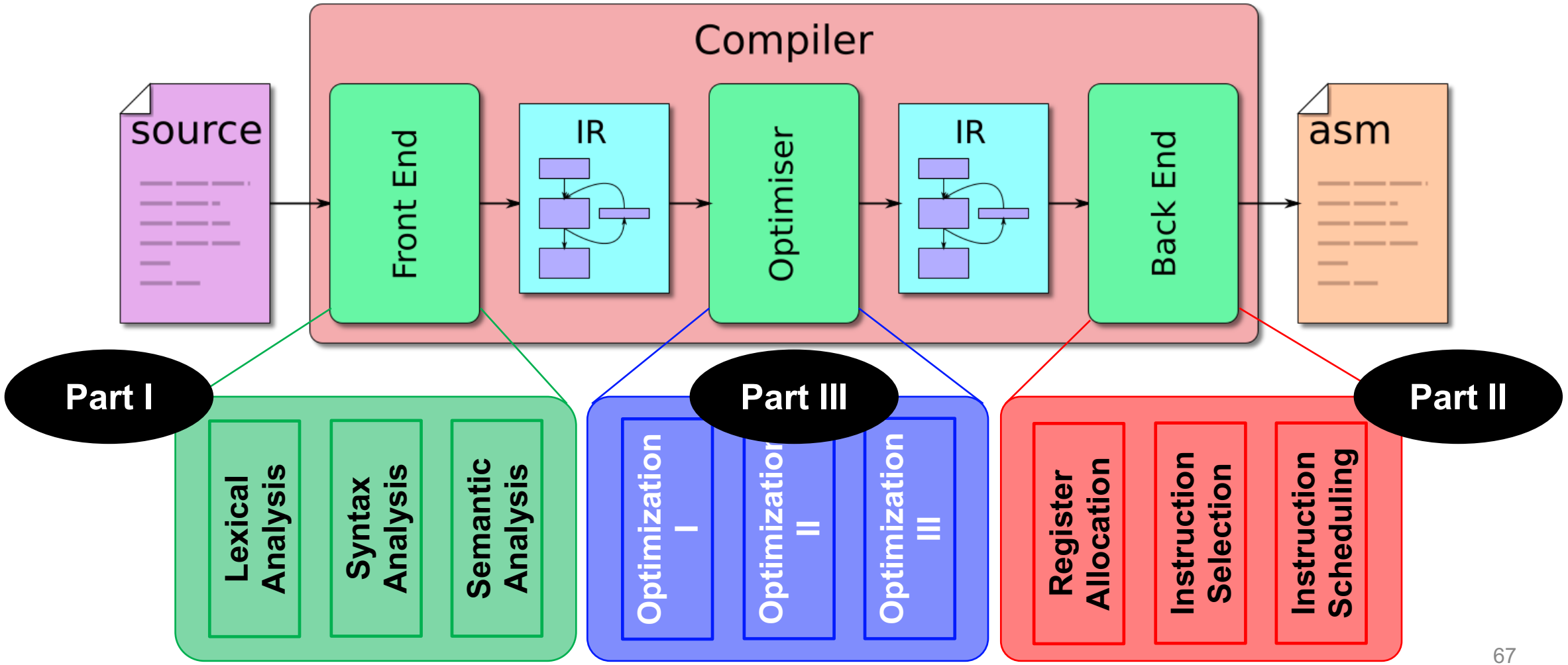
Back End: Instruction Scheduling

- Target machines often provide hardware resources for instruction-level parallelism

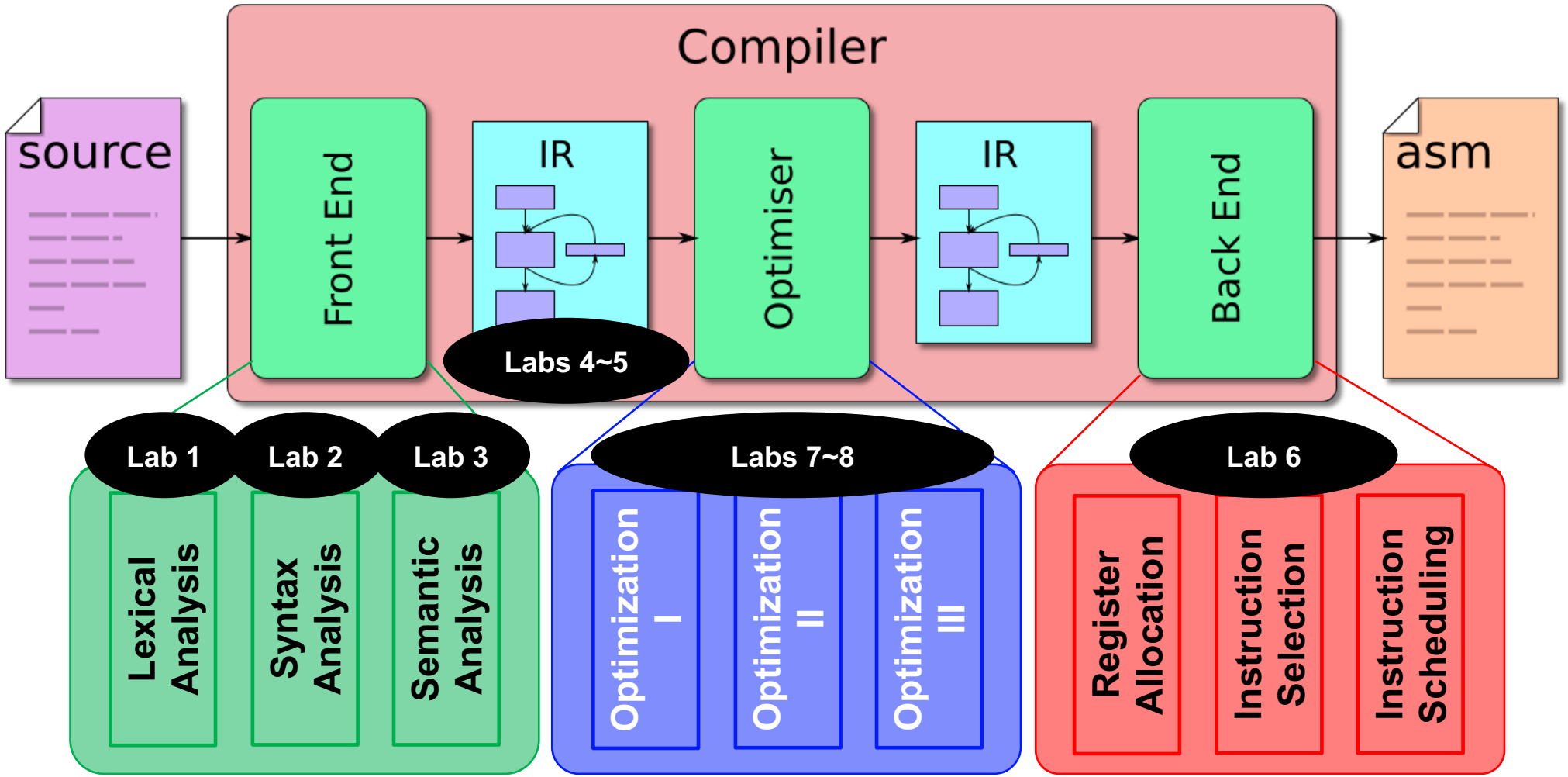
Back End: Instruction Scheduling

- Target machines often provide hardware resources for instruction-level parallelism
- Generating machine code to take advantage of such parallelism

Course Structure



Labs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Labs 4~5
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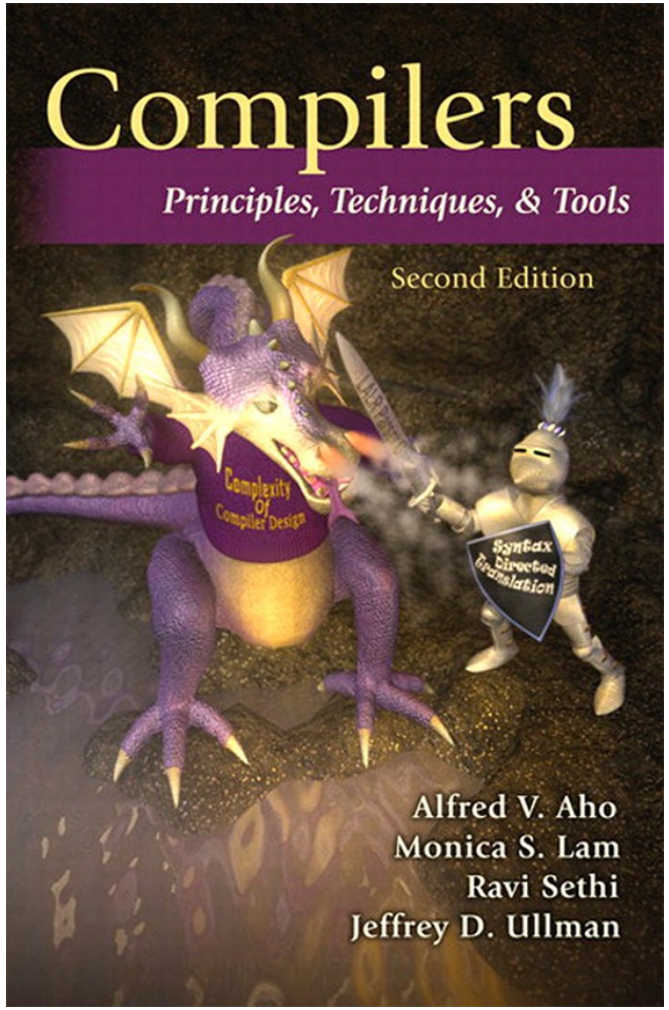
Lab 2
Lab 3
Lexical Analysis
Syntax Analysis
Semantic Analysis
Labs 7~8
Optimization I
Optimization II
Optimization III
Lab 6
Register Allocation
Instruction Selection
Instruction Scheduling

Course Homepage

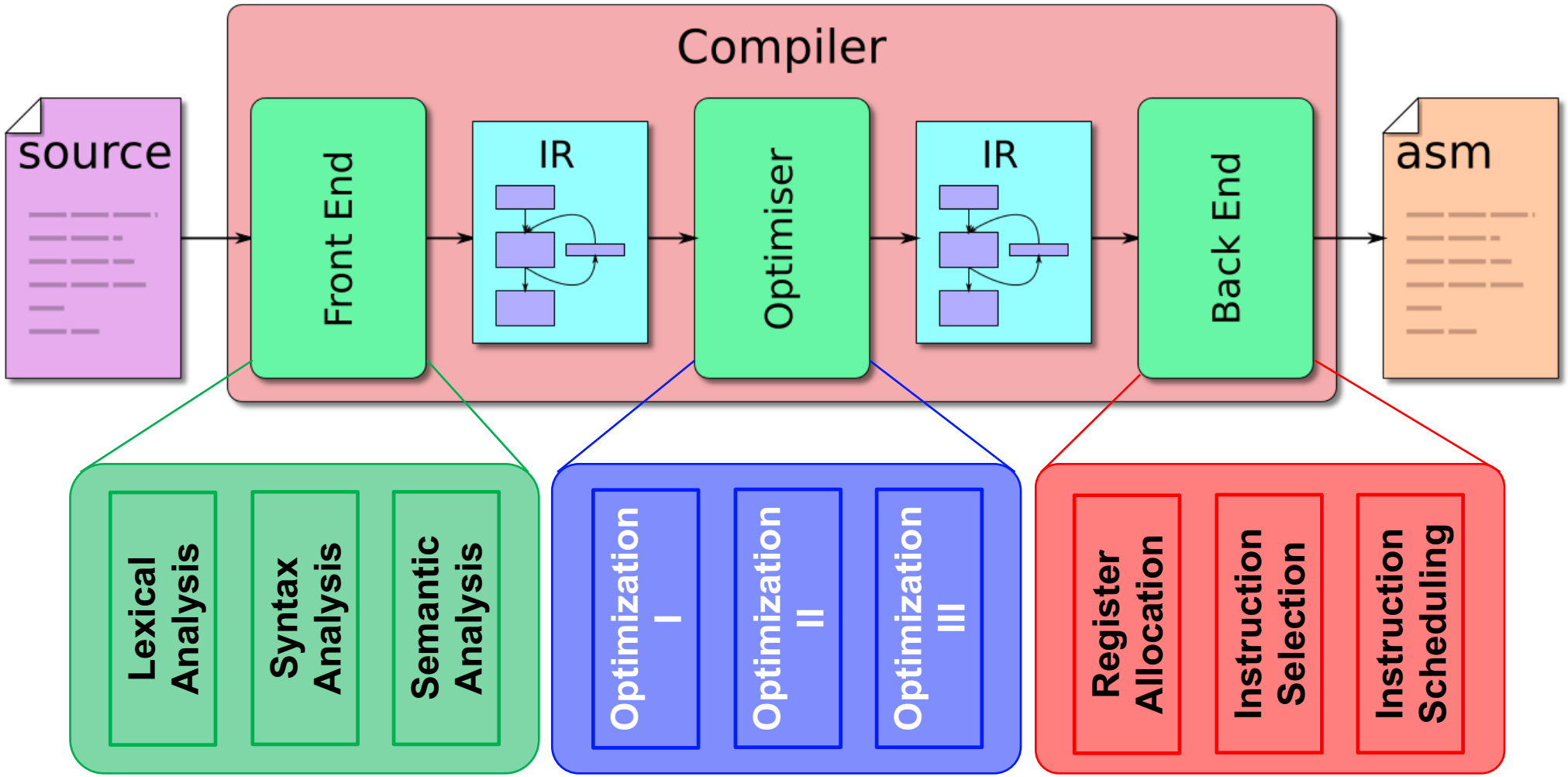
https://qingkaishi.github.io/Compilers.html

- Find additional info about the course in the course homepage
  - QQ Group
    - 1033582067
  - Grading Scheme
    - Assignments (0%)
    - Labs (70%)
    - Final Exam (30%)
  - Slides …



PART II: Tools

Tools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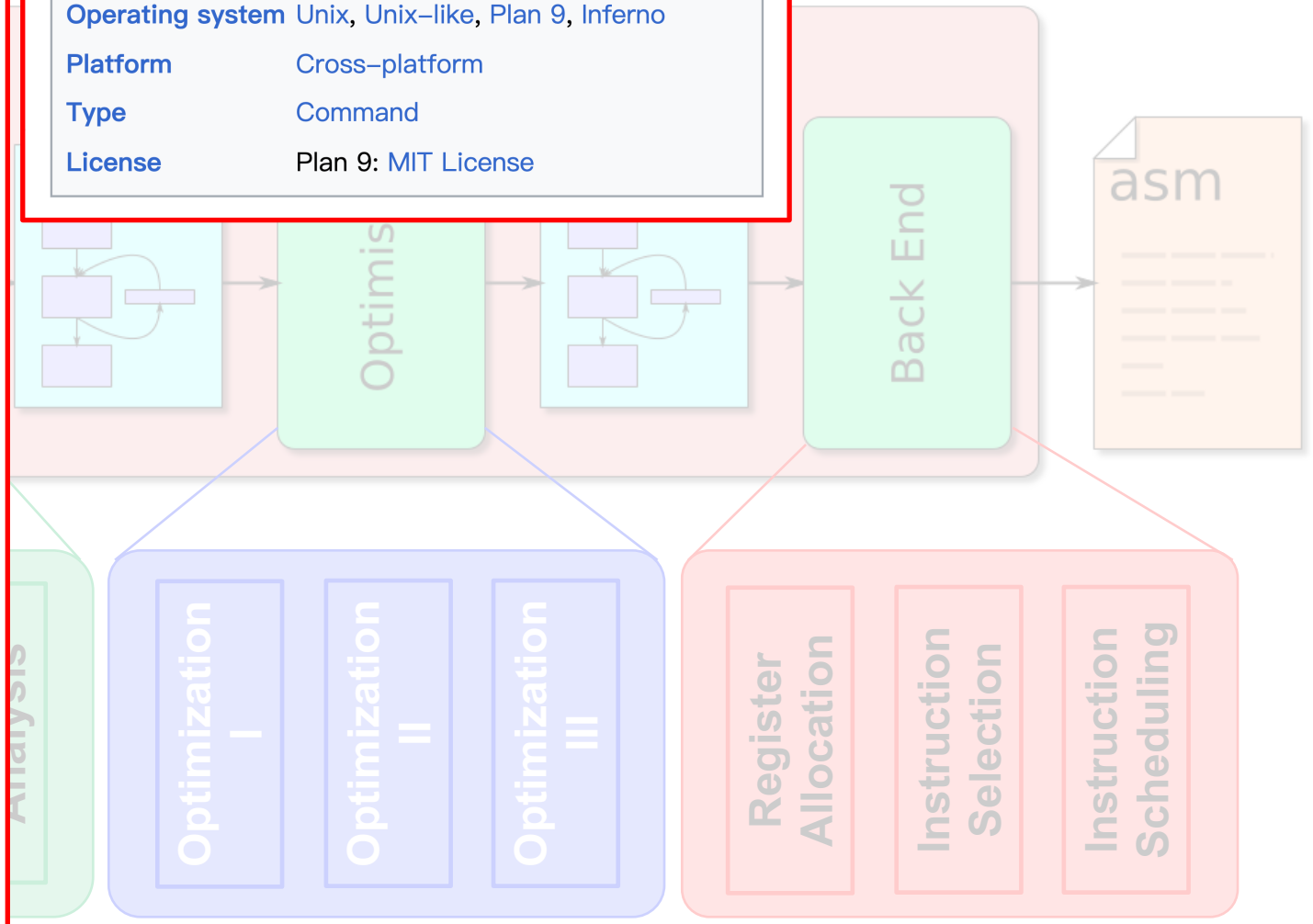
Tools

Yacc

Original author(s)	Stephen C. Johnson
Repository	www.tuhs.org/cgi-bin/utree.pl?file=V6%2Fusr%2Fsource%2Fyacc
Written in	C
Operating system	Unix, Unix-like, Plan 9, Inferno
Platform	Cross-platform
Type	Command
License	Plan 9: MIT License

GNU Bison

Original author(s)	Robert Corbett
Developer(s)	The GNU Project
Initial release	June 1985; 38 years ago[1]
Stable release	3.8.2[2] / 25 September 2021
Repository	git.savannah.gnu.org/cgit/bison.git
Written in	C and m4
Operating system	Unix-like
Type	Parser generator
License	GPL
Website	www.gnu.org/software/bison/



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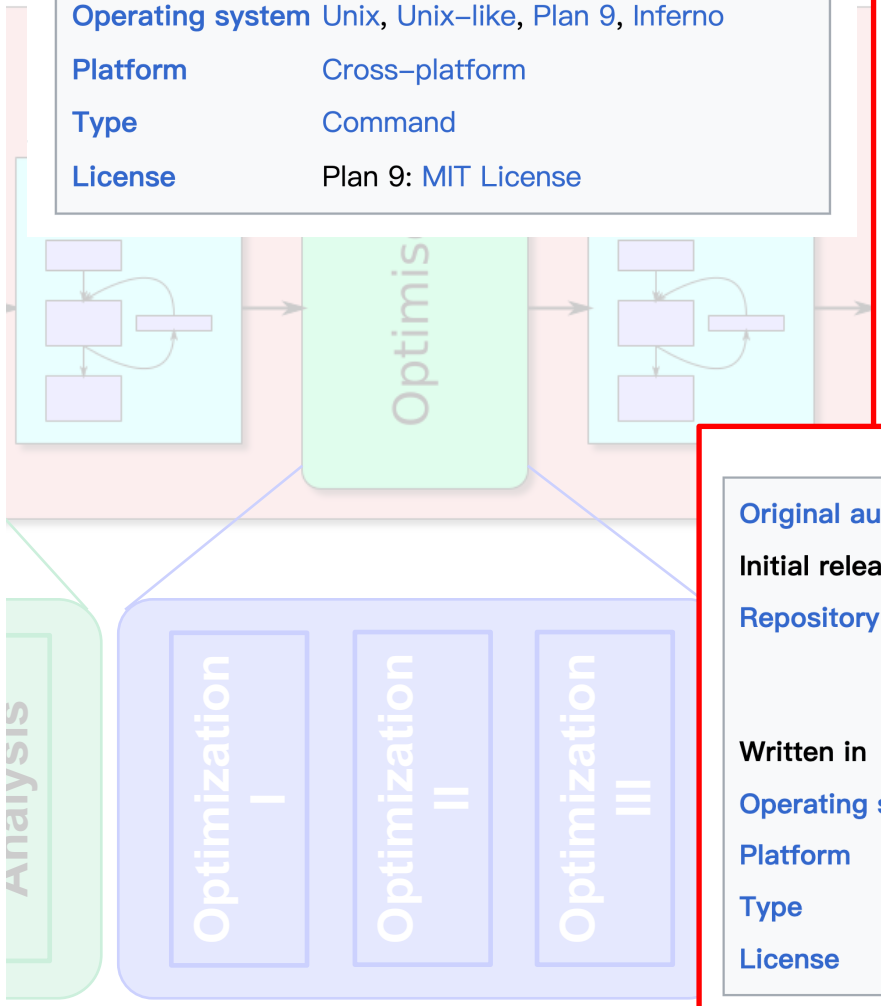

flex

Developer(s)	Vern Paxson
Initial release	around 1987; 37 years ago[1]
Stable release	2.6.4 / May 6, 2017; 6 years ago
Repository	github.com/westes/flex.git
Operating system	Unix-like
Type	Lexical analyzer generator
License	BSD license
Website	github.com/westes/flex

Lex

Original author(s)	Mike Lesk, Eric Schmidt
Initial release	1975; 49 years ago
Repository	minnie.tuhs.org/cgi-bin/utree.pl?file=4BSD%2Fusr%2Fsrc%2Fcmd%2Flex
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编译技术
全研究组

PART III: Applications

Applications

- Implementation of High-Level Programming Languages

Applications

- Implementation of High-Level Programming Languages

VERILOG

VHDL

P4

Domain Specific Language

Applications

- Implementation of High-Level Programming Languages
- **Design & Optimization of Computer Architectures**
  - AI, Gaming, Embedded Systems, High Performance Computing, …

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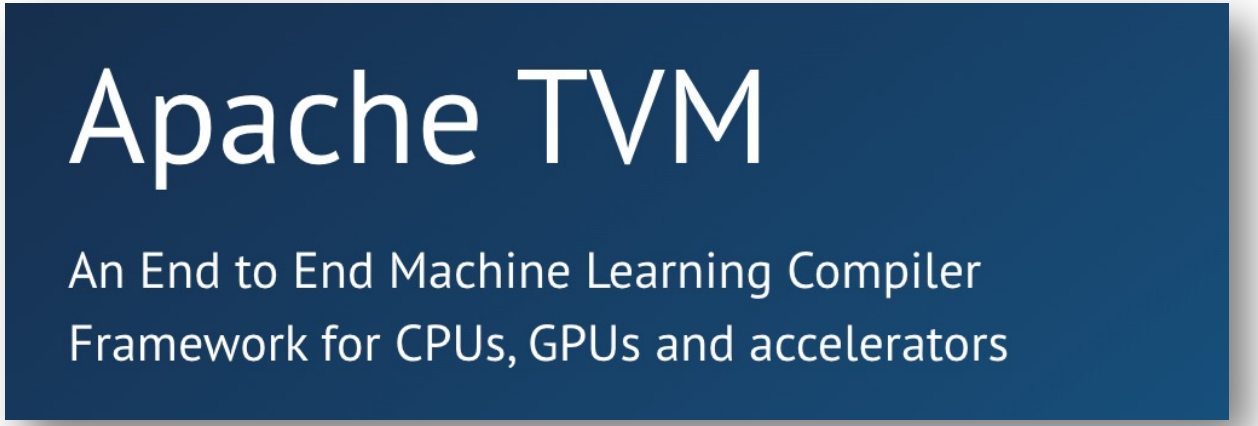

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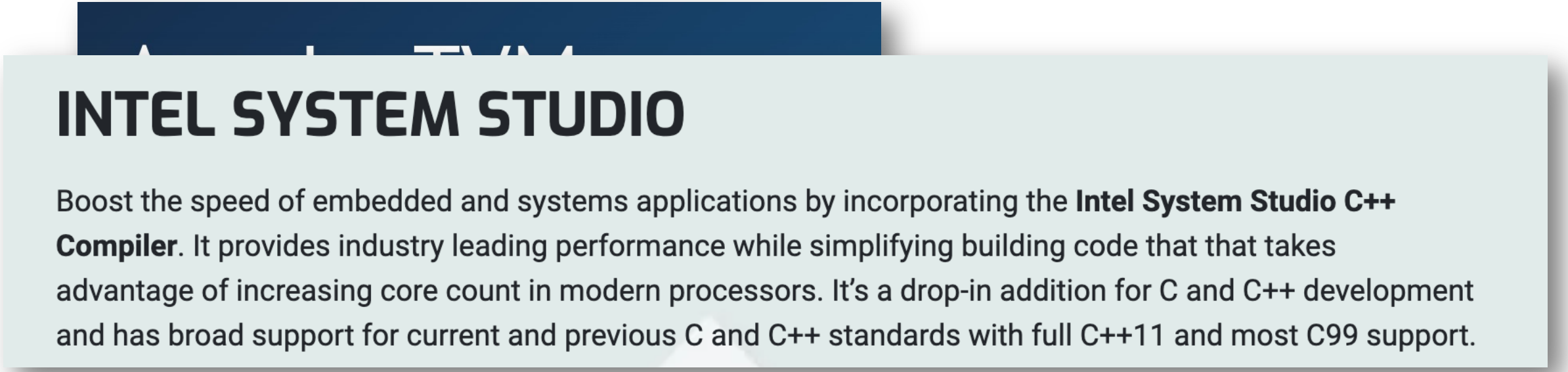

Applications

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NVIDIA HPC Fortran, C++ and C Compilers with OpenACC

Using NVIDIA HPC compilers for NVIDIA data center GPUs and X86-64, OpenPOWER and Arm Server multi-core CPUs, programmers can accelerate science and engineering applications using Standard C++ and Fortran parallel constructs, OpenACC directives and CUDA Fortran.

Applications

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Biden: “All non-Rust projects are illegal”

”Programmers do not write code without consequence, and the way they do it is critical to the national interest.”

Aaron 0928 · Follow

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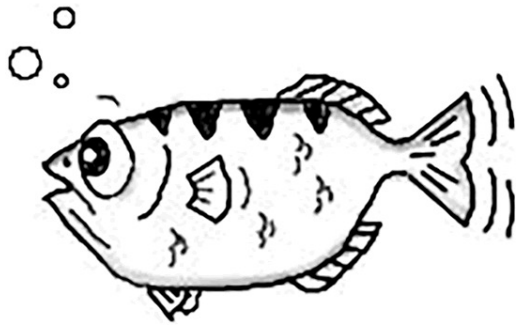

GDB
The GNU Project Debugger

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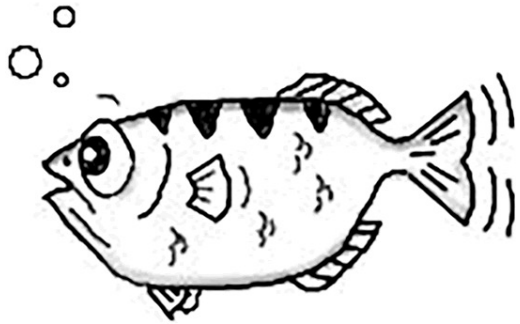

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JProfiler

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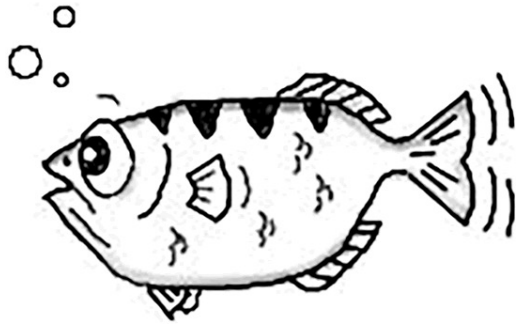

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JACOCO
Java Code Coverage

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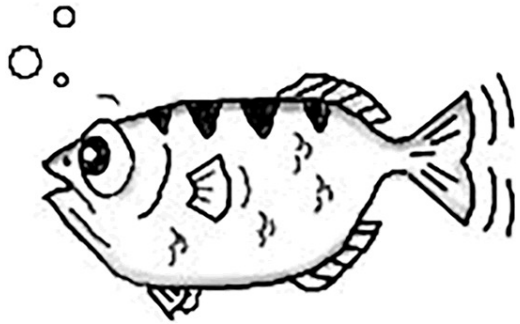

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Clang Power Tools

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Clang
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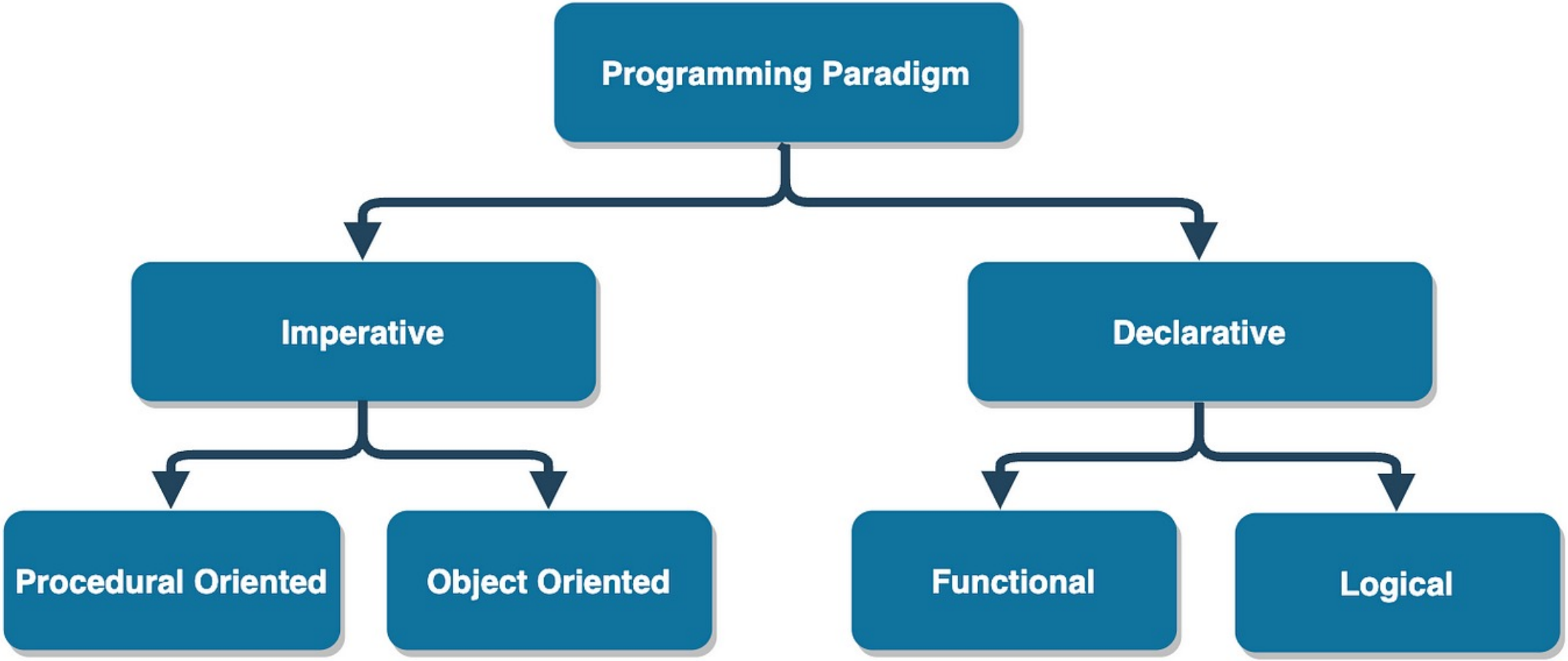
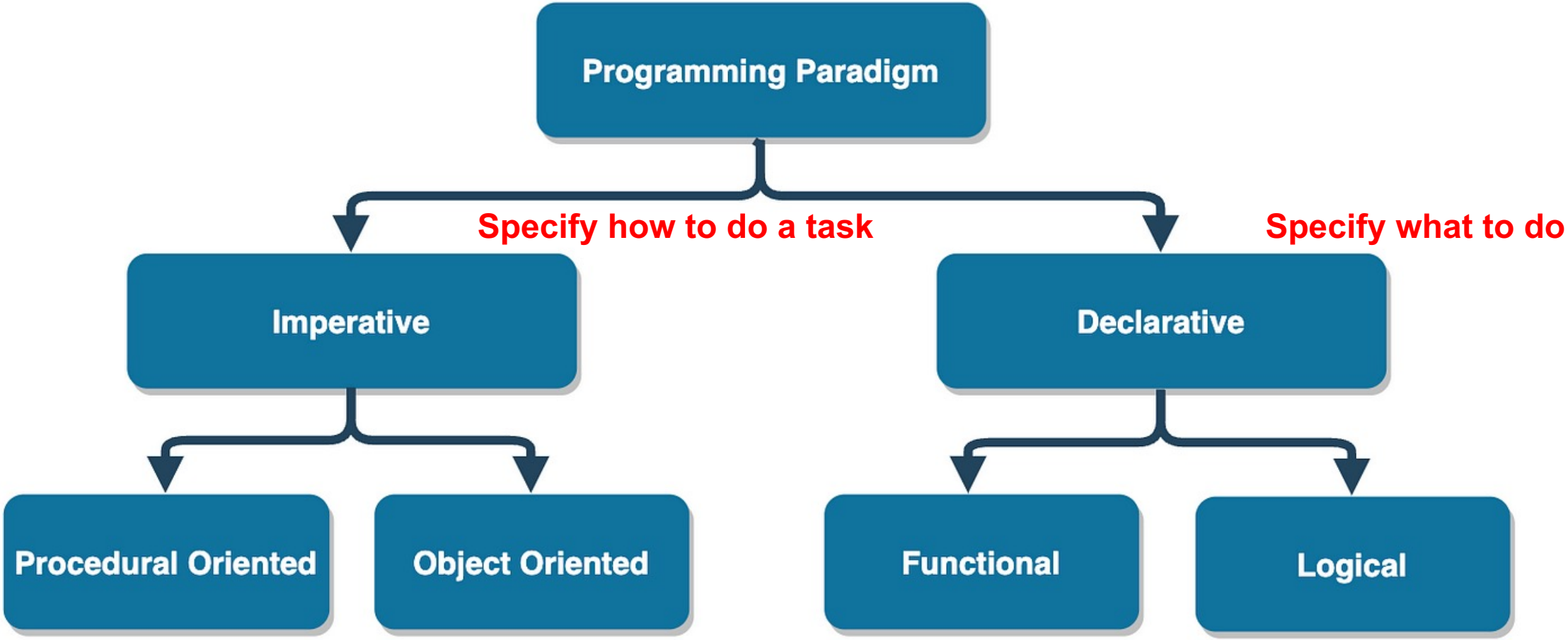
PART IV: Terminologies Review

Programming Languages



Programming Languages



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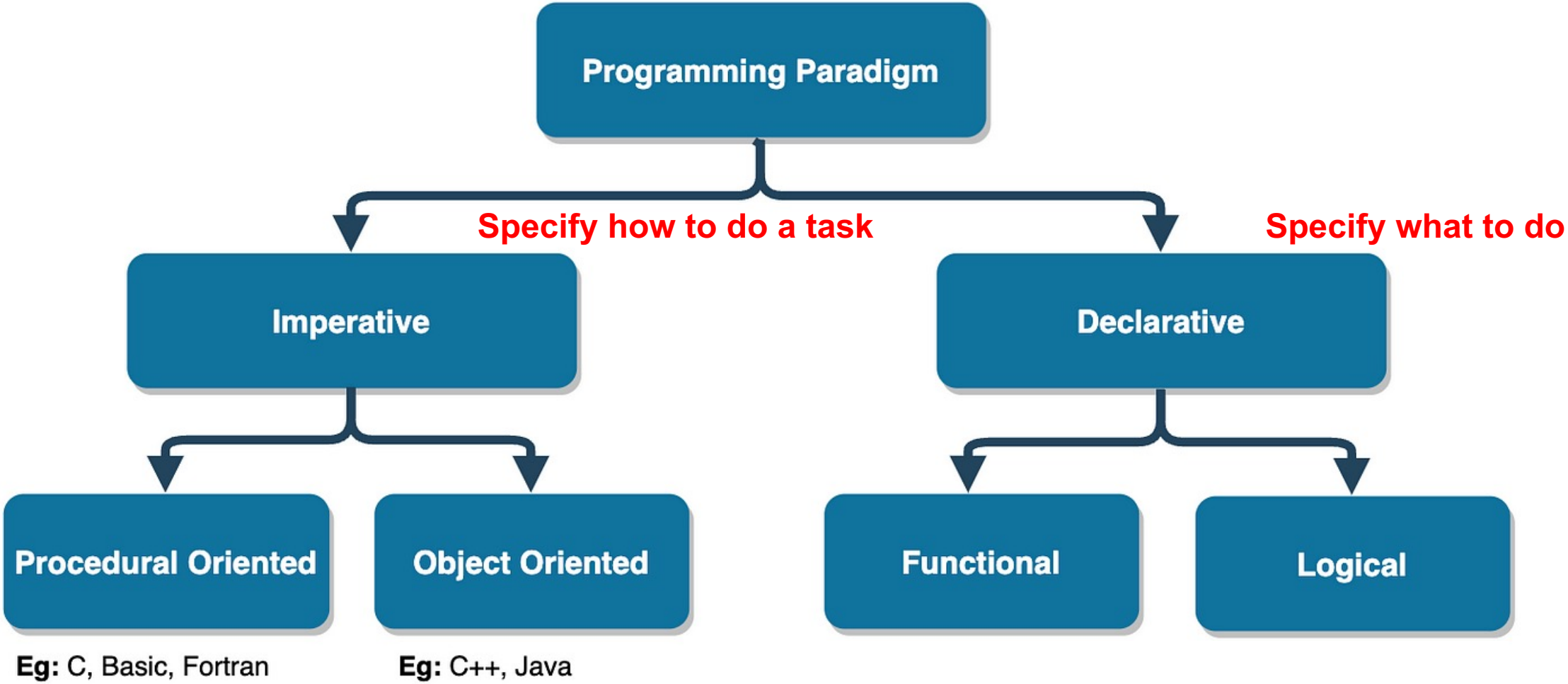

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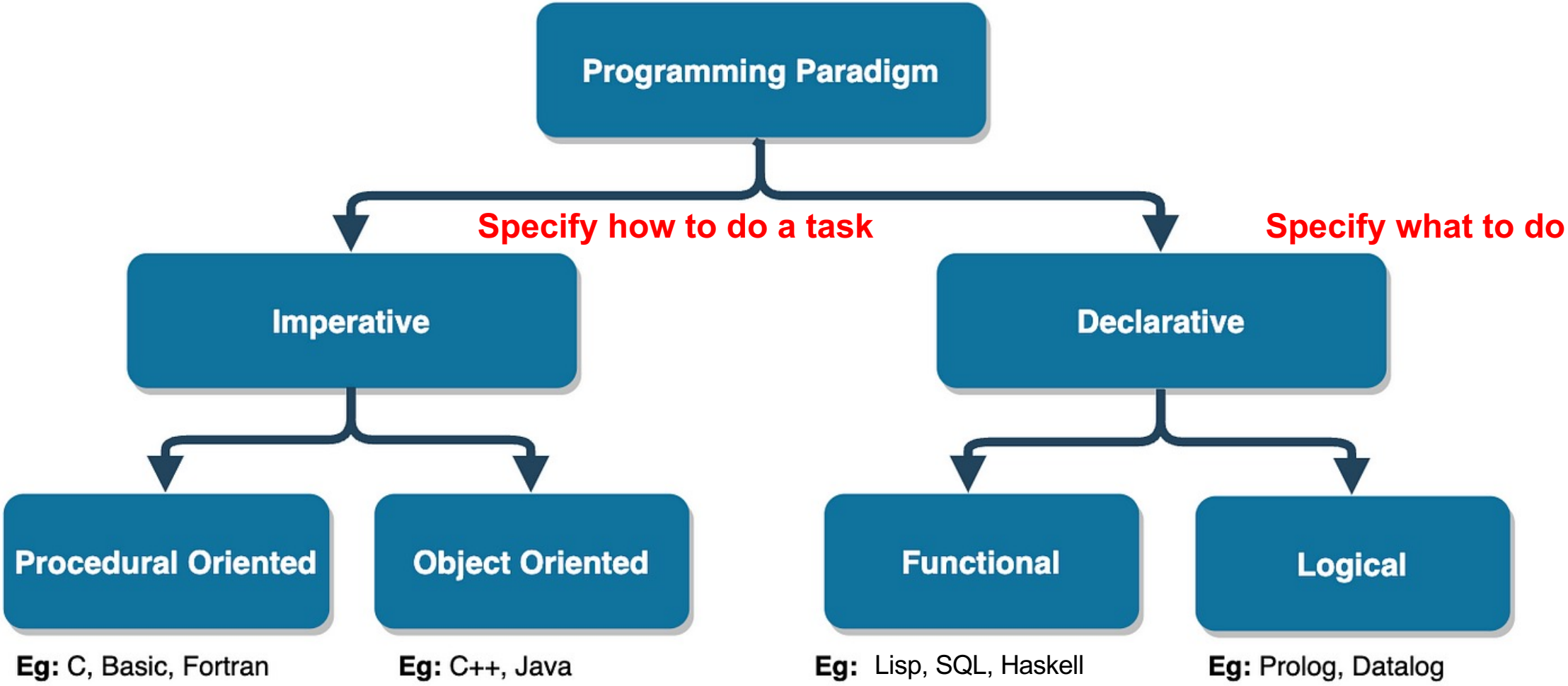

Functional Programming

Functional Programming

- Functional programming contains **only functions** without mutating the state or data.
  - It means that there are **no global data/variables**.

Functional Programming

- Functional programming contains only functions without mutating the state or data.
- Composing and applying functions is the main driving force in this paradigm.

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```
select
    sum(case when some_flag = 'X' then some_column else other_column end)
from ...
```

Functional Programming

- Functional programming contains only functions without mutating the state or data.
- Composing and applying functions is the main driving force in this paradigm.
- A function can take another as an argument and return a new function.

Logic Programming

Logic Programming

- The Logical paradigm has its foundations in mathematical logic in which we declare **facts** and **rules**

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  - **Fact:** Nanjing is rainy
  - **Fact:** Beijing is rainy; Beijing is cold
  - **Rule:** If a city is both rainy and cold, then it is snowy

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  - **Fact:** Nanjing is rainy
  - **Fact:** Beijing is rainy; Beijing is cold
  - **Rule:** If a city is both rainy and cold, then it is snowy

```
1.  rainy(“Nanjing”)
2.  rainy(“Beijing”);
3.  cold(“Beijing”)
4.  snowy(c) :- rainy(c),  cold(c)
5.  .output snowy
```

Type Systems

- Static vs. Dynamic Typing
- Strong vs. Weak Typing

Type Systems

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  - is about when type information is acquired (at compile time or runtime?)

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For example in Java:

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String str = "Hello";  //statically typed as string
str = 5;               //would throw an error since java is statically typed
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For example in Java:

```
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str = 5;               //would throw an error since java is statically typed
```

For example in Python:

```
str = "Hello" # it is a string
str = 5       # now it is an integer; perfectly OK
```

Type Systems

- **Strong vs. Weak Typing**
  - is about how strictly types are distinguished (e.g. whether the language can do an **implicit conversion** from **strings** to **numbers**).

Type Systems

- **Strong vs. Weak Typing**
  - is about how strictly types are distinguished (e.g. whether the language can do an **implicit conversion** from strings to numbers).

For example in Python:

```
str = 5 + "hello"
# would throw an error since it does not want to cast one type to the other
```

whereas in PHP:

```
$str = 5 + "hello"; // equals 5 because "hello" is implicitly casted to 0
// PHP is weakly typed, thus is a very forgiving language.
```

Scoping

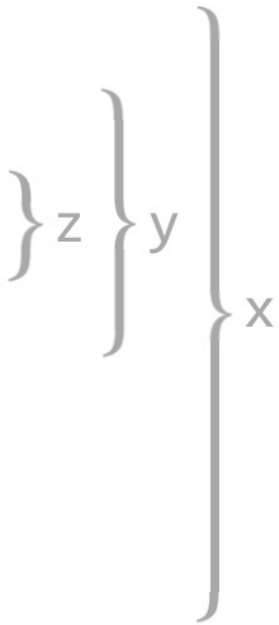
- Static vs. Dynamic scoping

Scoping

- Static vs. Dynamic scoping

```
/* C++ Example Code */
int x = 5;
if(x < 10) {
    int y = 20;
    if(x < 30) {
        int z = y*2;
    }
}

/* Print Contents of Variables */
cout << x << endl;  /* Ok, prints 5 */
cout << y << endl;  /* Error! */
cout << z << endl;  /* Error! */
```



Scoping

- Static vs. Dynamic scoping

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```

z, y, x

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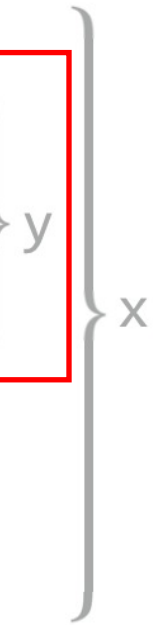
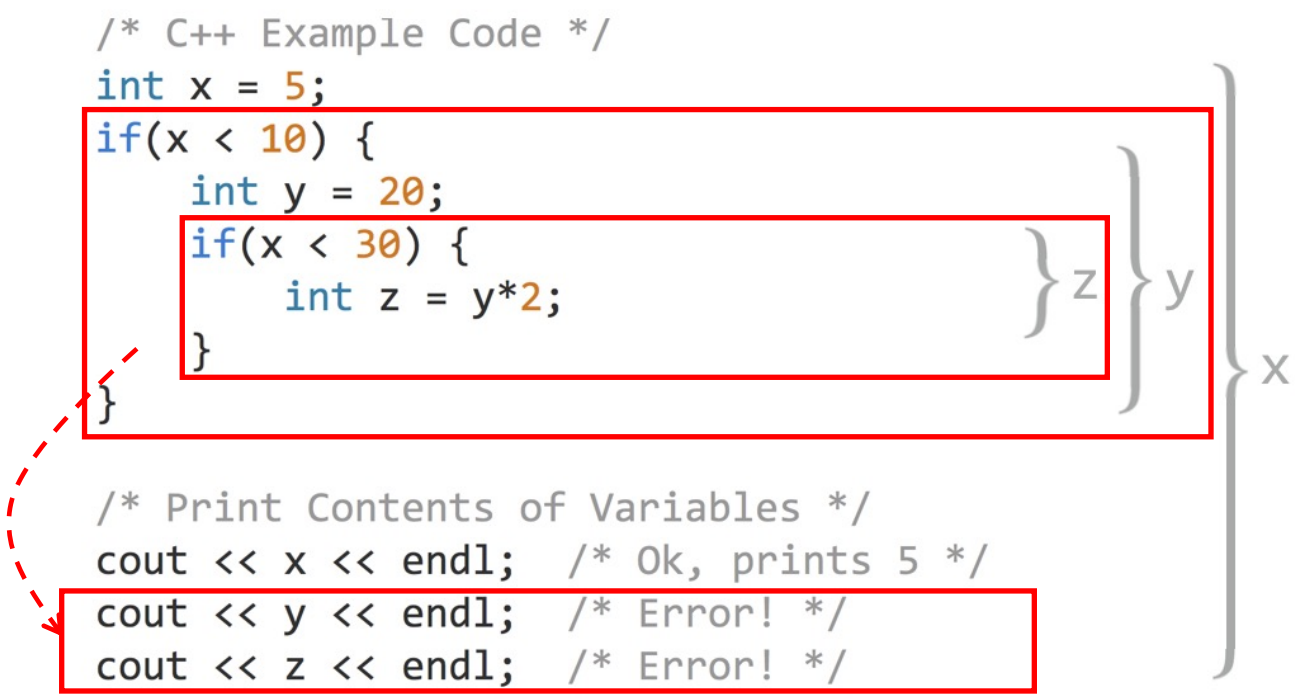


Scoping

- Static vs. Dynamic scoping

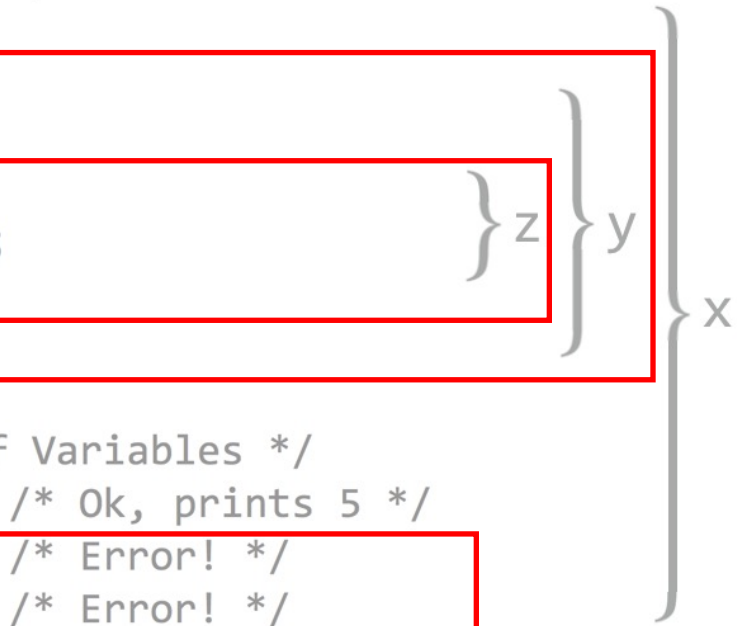


Scoping

- Static vs. Dynamic scoping

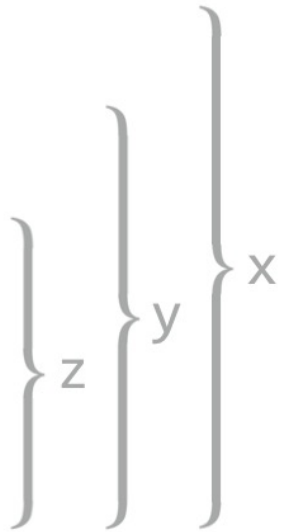
```cpp
/* C++ Example Code */
int x = 5;
if(x < 10) {
    int y = 20;
    if(x < 30) {
        int z = y*2;
    }
}

/* Print Contents of Variables */
cout << x << endl;  /* Ok, prints 5 */
cout << y << endl;  /* Error! */
cout << z << endl;  /* Error! */
```




```python
# Python Example Code
x = 5
if x < 10:
    y = 20
    if x < 30:
        z = y * 2

# Print Contents of Variables
print(x)  # Ok, prints 5
print(y)  # Ok, prints 20
print(z)  # Ok, prints 40
```



Function Invocation

- Call by value vs. Call by reference

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```
void swap(int x, int y)
{
    int t;

    t = x;
    x = y;
    y = t;
}
```

vs.

```
void swap(int &x, int &y)
{
    int t;

    t = x;
    x = y;
    y = t;
}
```

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void swap(int x, int y)
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    int t;

    t = x;
    x = y;
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}
```

vs.

```
void swap(int &x, int &y)
{
    int t;

    t = x;
    x = y;
    y = t;
}
```

```
int a = 5, b = 10; swap(a, b); printf("a = %d; b = %d", a, b);
```

Virtual Functions

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```
1.    void add(List<int> list, int y)
2.    {
3.        list.add(y); // ArrayList.add() or LinkedList.add()?
4.    }
```

Many many terminologies / features in a programming language!

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