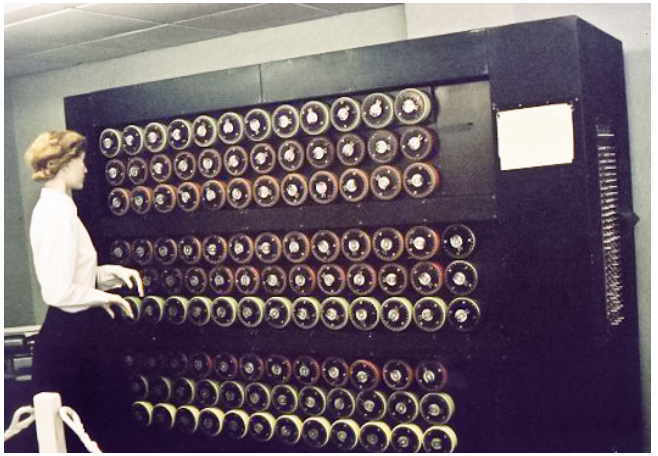
بسم الله الرحمن الرحيم

Introduction

- Course Information
- A Quick History of Compilers
- The Structure of a Compiler

What is a Compiler?

History of High-level Languages



A Short History of Compilers

- First, there was nothing.
- Then, there was machine code.
- Then, there were assembly languages.
- Programming expensive; 50% of costs for machines went into programming.

First Practical Compiler

In his PhD dissertation 1951; published in 1954), Böhm describes for the first time a translation mechanism of a programming language, written in that same language.

https://en.wikipedia.org/wiki/Corrado_B%C3%B6hm
https://en.wikipedia.org/wiki/B%C3%B6hm%27s_language

High-Level Languages

Rear Admiral **Grace Hopper**, inventor of COBOL, and the term "compiler."

Image: http://upload.wikimedia.org/wikipedia/commons/thumb/5/55/Grace_Hopper.jpg/300px-Grace_Hopper.jpg
http://www.nytimes.com/2007/03/20/business/20backus.html

High-Level Languages

Rear Admiral **Grace Hopper**, inventor of COBOL, and the term "compiler."

A programming language based on English

Image: http://upload.wikimedia.org/wikipedia/commons/thumb/5/55/Grace_Hopper.jpg/300px-Grace_Hopper.jpg
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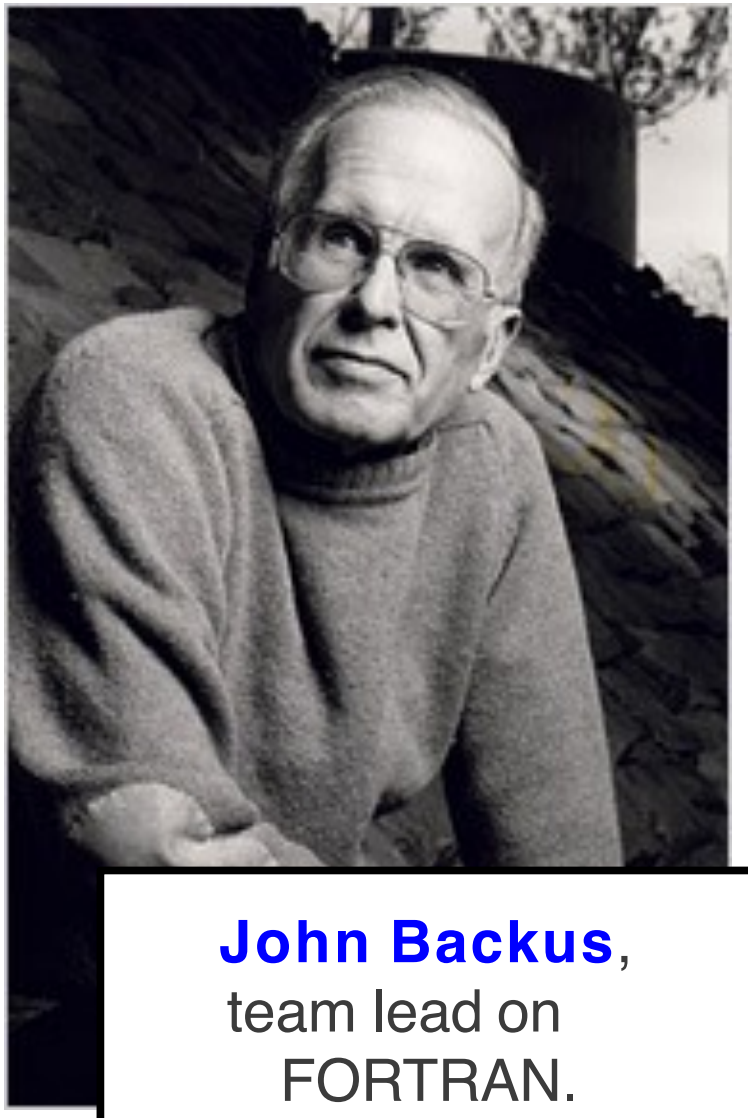
High-Level Languages



John Backus, team lead on FORTRAN.

Image: http://upload.wikimedia.org/wikipedia/commons/thumb/5/55/[illegible]er.jpg
http://www.nytimes.com/2007/03/20/business/20backus.html

FORTRAN I

- Translate high-level code to assembly.
- Many thought this impossible.
- Had already failed in other projects.
- Development time halved
- Performance is close to hand-written assembly!

Effect on Computer Science

- The first compiler
- Huge impact on computer science.
- Led to an enormous body of theoretical and practical work.
- Modern compilers preserve the outlines of FORTRAN I

```
INTEGER FUNCTION FCN20(NDIMS, X, NFCNS, FUNVLS)
    INTEGER NDIMS, NFCNS
    DOUBLE PRECISION X(*), FUNVLS(*)
    DOUBLE PRECISION Z
    Z = (X(1) + X(2) + X(3)) ** 2
    IF (Z .NE. 0.0) THEN
       FUNVLS(1) = 1.0 / Z
    ELSE
       FUNVLS(1) = 0.0
    ENDIF
    FCN20 = 1
    RETURN
END
```

What is a Compiler?

- Takes as input a program written in one language and **translates** it into a **functionally equivalent** program in another language.
- Source is usually high-level (e.g. Java), target is usually low-level (e.g. Assembly).
-

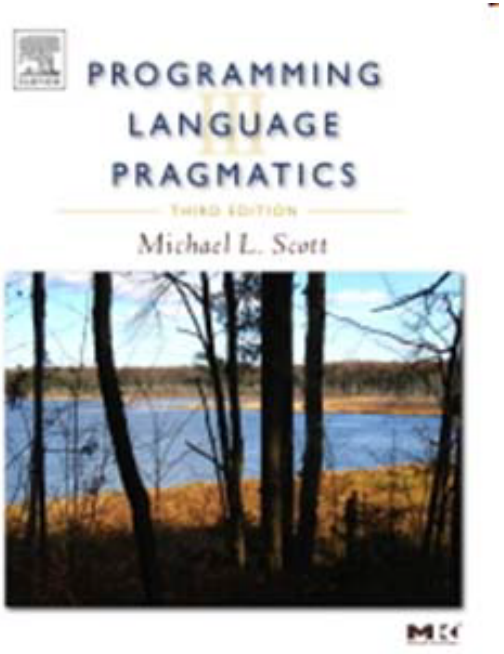
Hierarchy of dependency between concepts related to compiler

- computational model
- programming language
- compiler

Computational Thinking in Programming Language Design

Underlying every programming language is a model of computation:

- **Procedural: C, C++, C#, Java**
- **Declarative: SQL**
- **Logic: Prolog**
- **Functional: Haskell**
- **Scripting: AWK, Perl, Python, Ruby**



Evolutionary Forces on Languages and Compilers

More and different kinds of languages

Increasing diversity of applications

Stress on increasing productivity

Need to improve software reliability

Target machines more diverse

Parallel machine architectures

Massive compiler collections

1970	2010
Fortran	Java
Lisp	C
Cobol	PHP
Algol 60	C++
APL	Visual Basic
Snobol 4	C#
Simula 67	Python
Basic	Perl
PL/1	Delphi
Pascal	JavaScript

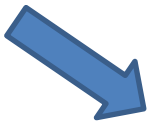
[http://www.tiobe.com]

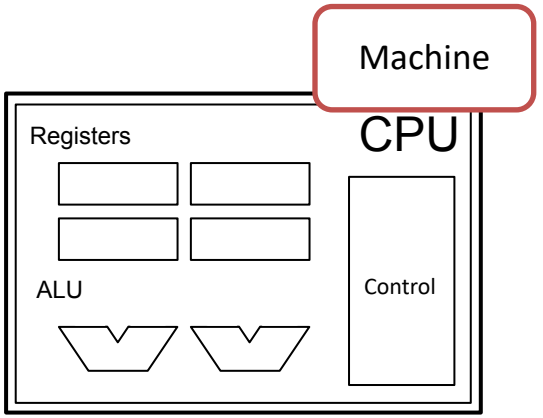
Schema

Language

```
fun(y) {
  x = y - 2;
  return x;
};
```

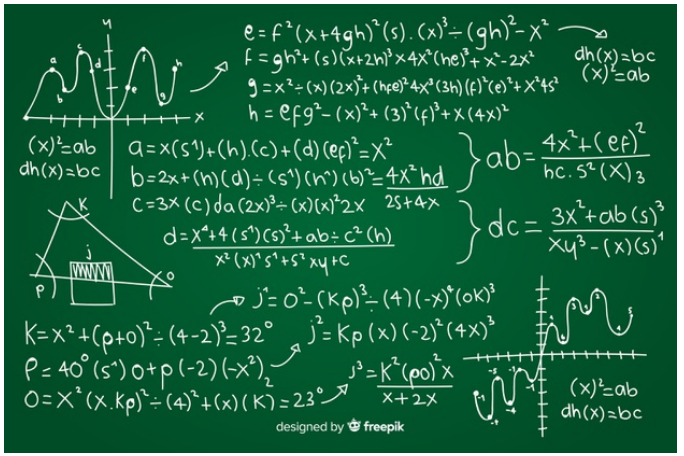
Infinite resources
No performance specification





- Finite resources
- Extremely performance sensitive

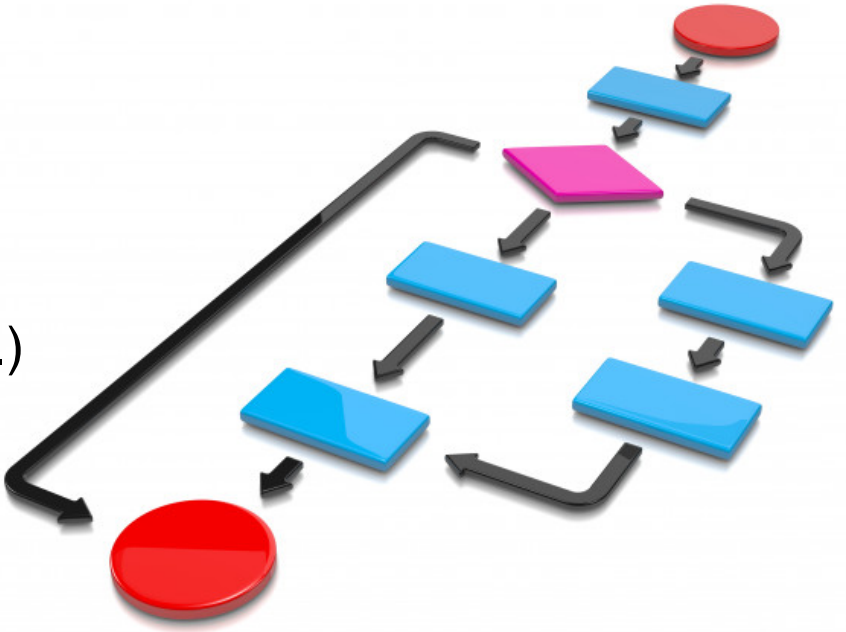
Language Environment Construction touches many topics in Computer Science



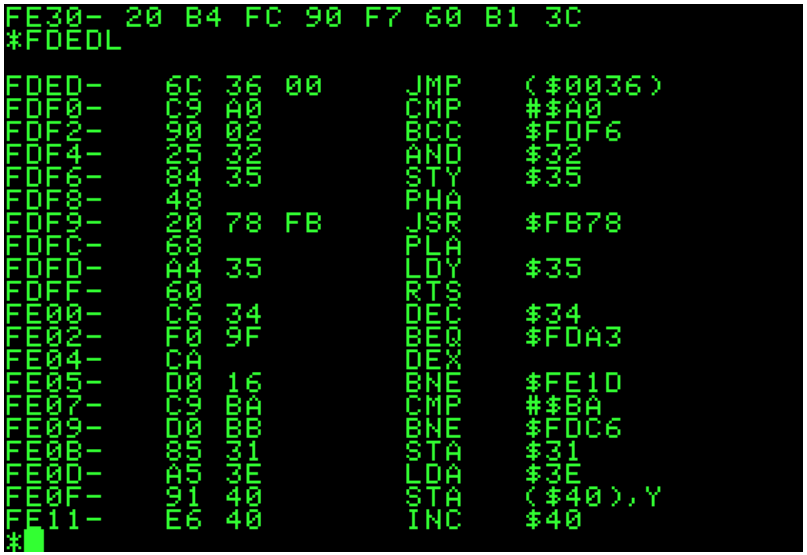
- Theory
  - Finite State Automata, Grammars and Parsing, data-flow
- Algorithms
  - Graph manipulation, dynamic programming
- Data structures
  - Symbol tables, abstract syntax trees
- Systems
  - Allocation and naming, multi-pass systems, compiler construction
- Computer Architecture
  - Memory hierarchy, instruction selection, interlocks and latencies, parallelism
- Security
  - Detection of and Protection against vulnerabilities
- Software Engineering
  - Software development environments, debugging
- Artificial Intelligence
  - Heuristic based search for best optimizations

Inputs

- Standard language
  - State
    - Variables,
    - Structures,
    - Arrays
  - Computation
    - Expressions (arithmetic, logical, etc.)
    - Assignment statements
    - Control flow (conditionals, loops)
    - Procedures



Outputs



- State
  - Registers
  - Memory with Flat Address Space
- Machine code – load/store architecture
  - Load, store instructions
  - Arithmetic, logical operations on registers
  - Branch instructions

Translation Approaches

- Compiler Approach
- Interpreter Approach
- Dynamic Approach

Compiler Approach

Compiler Approach

- The target is not necessarily a machine code.
  - e.g. Assembly language e.g. MIPS or x86
  - e.g. VHDL: the output is C.
  - It might be intermediate code e.g. JBC

Compiler Approach

- The target is not necessarily a machine code.
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- By following **physical structure** of program we translate it.

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- The generated code is much more faster.

Compiler Approach

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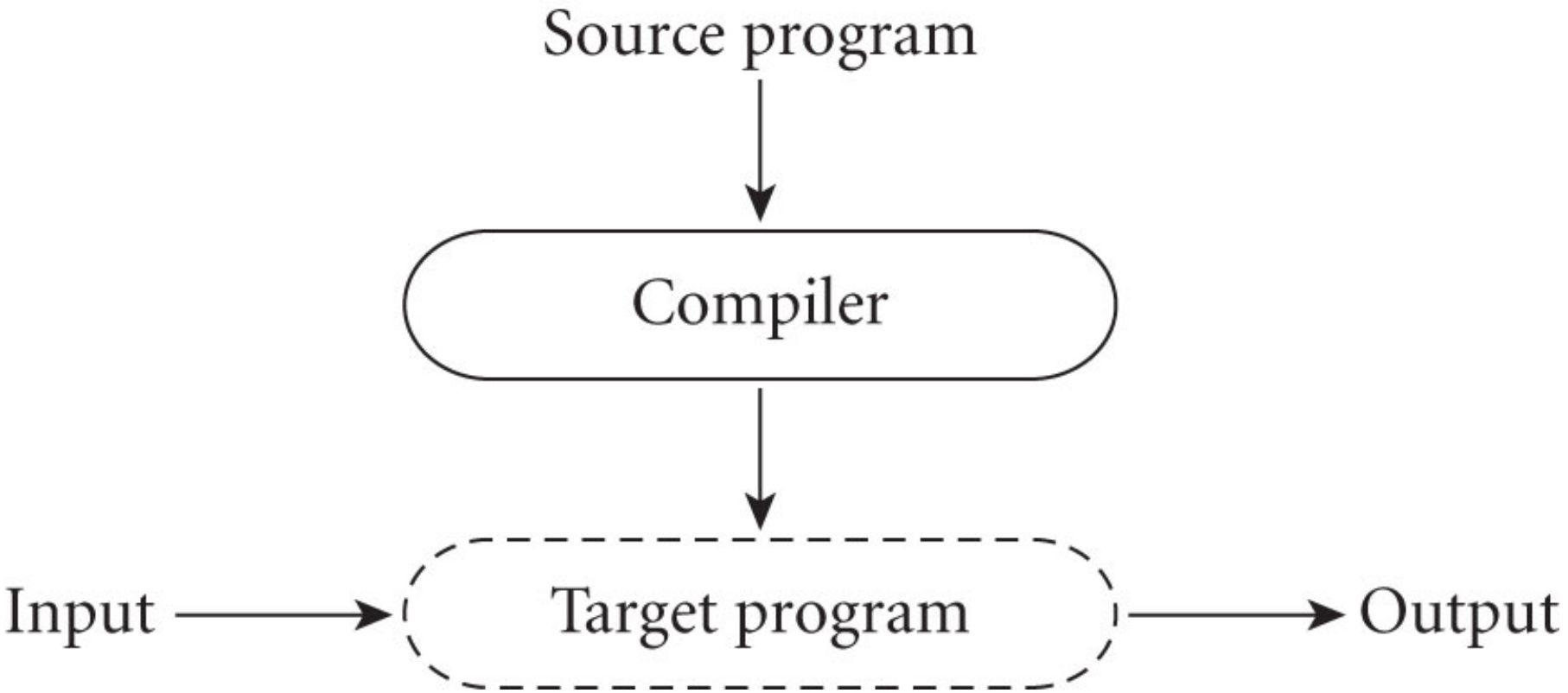
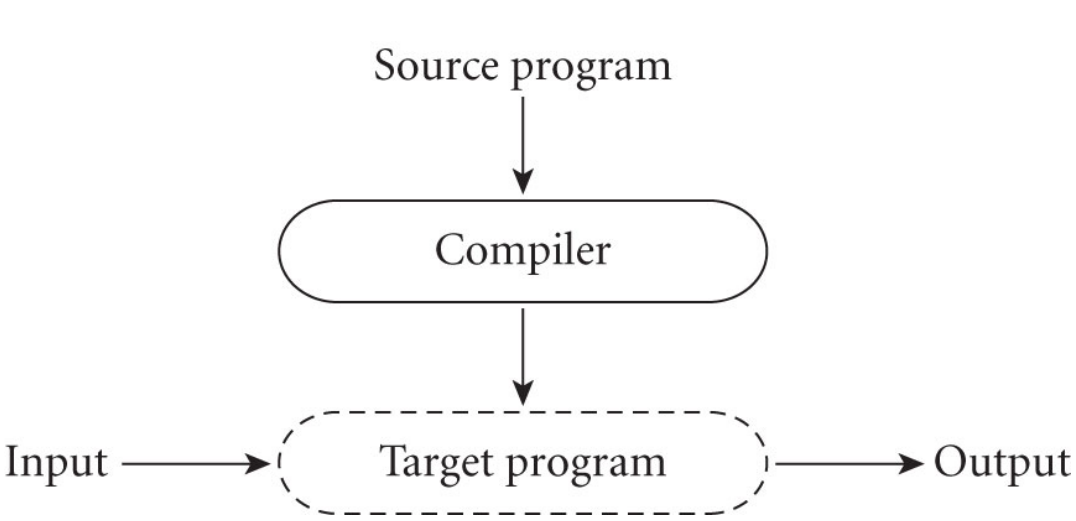
  - e.g. VHDL: the output is C.
  - It might be intermediate code e.g. JBC
- By following **physical structure** of program we translate it.
- The generated code is much more faster.
- We decide before run the code (e.g. type)


Source program
Compiler
Input
Target program
Output

```c
#include <stdio.h>

int getint() {
    int i;
    scanf("%d", &i);
    return i;
}

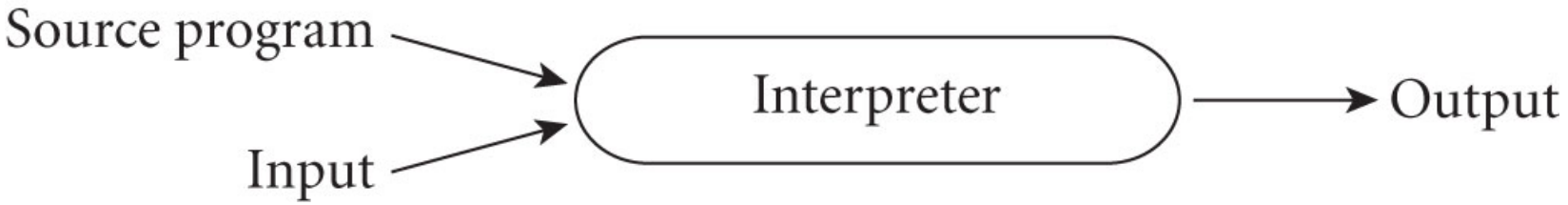
int gcd() {
    int i = getint(), j = getint(
);
    while (i != j) {
        if (i > j) i = i - j;
        else j = j - i;
    }
     return I;
}
```




```
.LC0:
        .string "%d"
getint():
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
        lea     rax, [rbp-4]
        mov     rsi, rax
        mov     edi, OFFSET FLAT:.LC0
        mov     eax, 0
        call    __isoc99_scanf
        mov     eax, DWORD PTR [rbp-4]
        leave
        ret
.LC1:
        .string "%d\n"
putint(int):
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
        mov     DWORD PTR [rbp-4], edi
        mov     eax, DWORD PTR [rbp-4]
        mov     esi, eax
        mov     edi, OFFSET FLAT:.LC1
        mov     eax, 0
        call    printf
        leave
        ret
main:
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
        call    getint()
        mov     DWORD PTR [rbp-4], ea
x
        call    getint()
        mov     DWORD PTR [rbp-8], ea
x
        jmp     .L5
.L7:
        mov     eax, DWORD PTR [rbp-4
]
        cmp     eax, DWORD PTR [rbp-8
]
        jle     .L6
        mov     eax, DWORD PTR [rbp-8
]
        sub     DWORD PTR [rbp-4], ea
x
        jmp     .L5
.L6:
        mov     eax, DWORD PTR [rbp-4
]
        sub     DWORD PTR [rbp-8], ea
x
.L5:
        mov     eax, DWORD PTR [rbp-4
]
```

Interpreter Approach

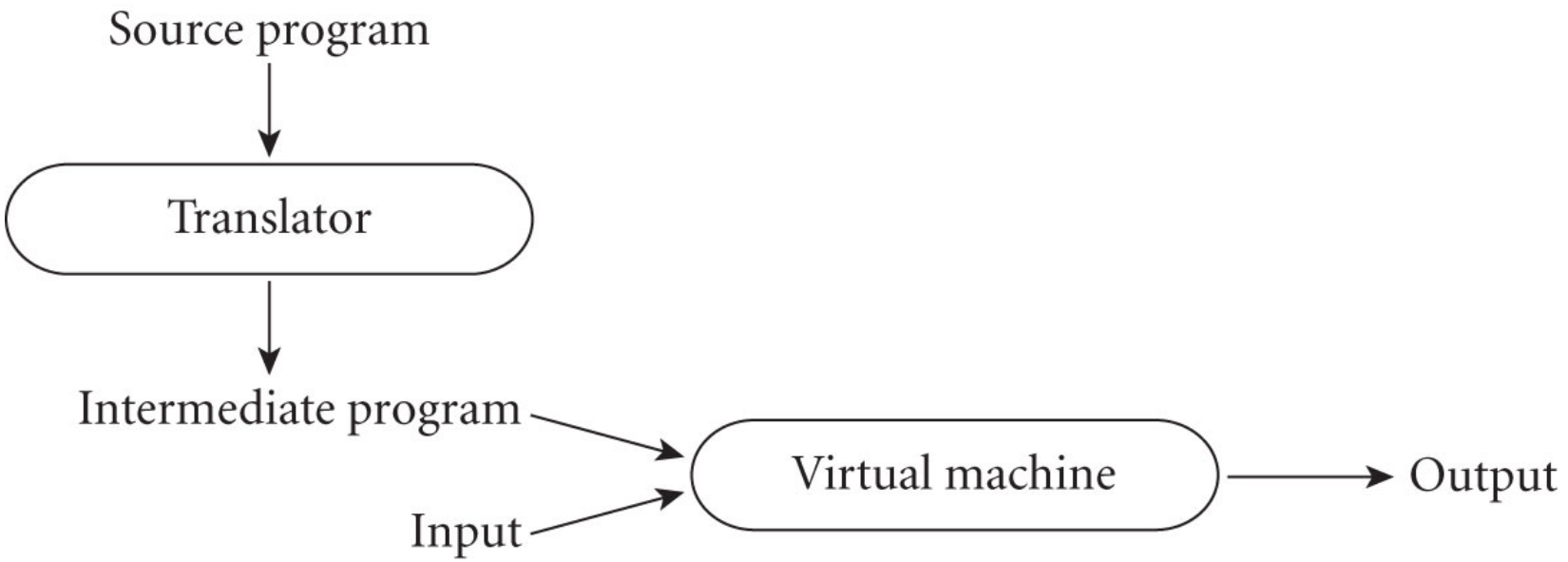
- Interpreter **translate** the source code to machine code **online**.
- The code is **translated** while it is **running.**



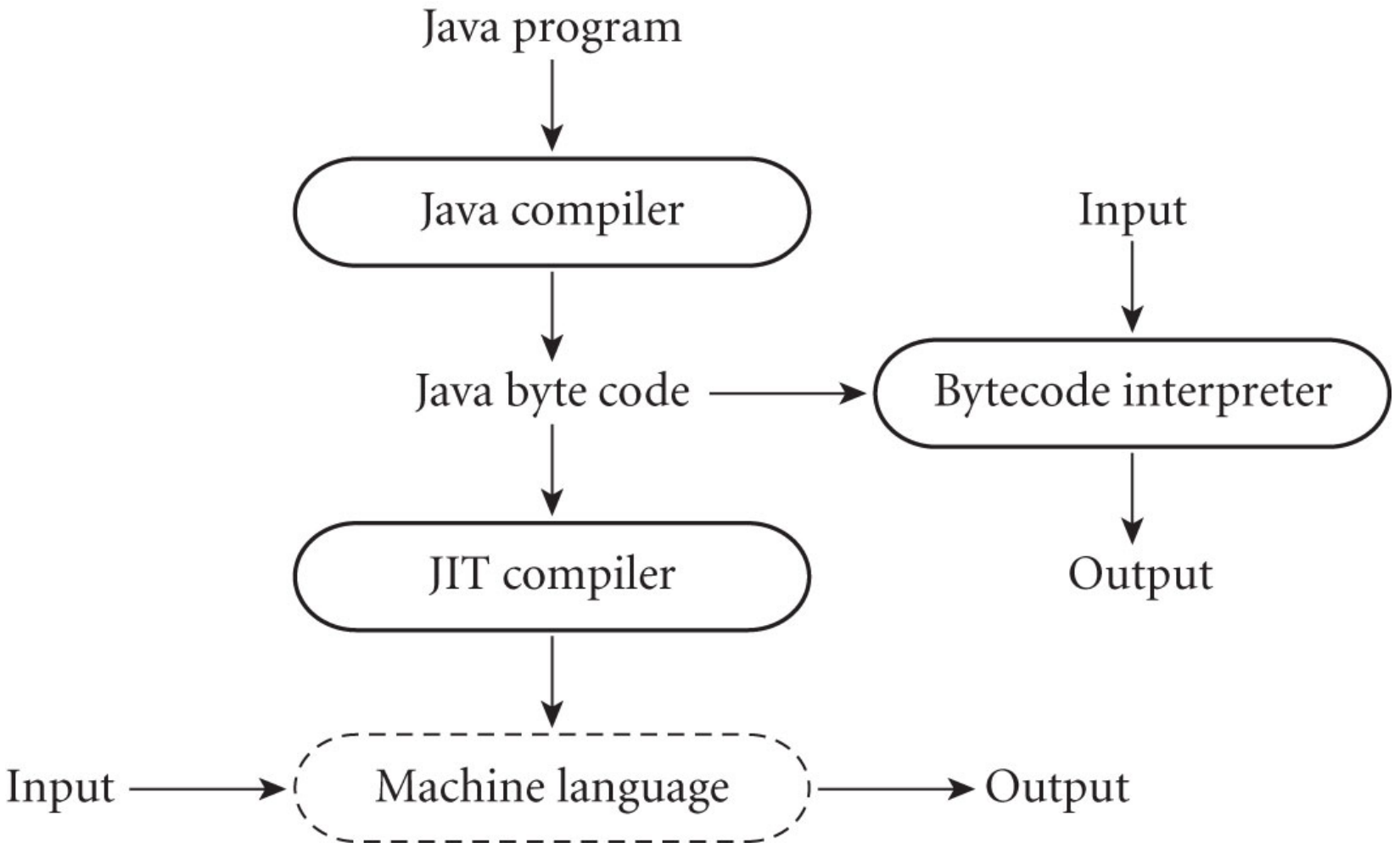
Interpreter Approach

- We follow the **execution path** to translate the code.
- leads to greater **flexibility** and better **diagnostics** (error messages) than does compilation.
- It can also cope with languages in which fundamental characteristics of the program, such as the sizes and types of variables, or even which names refer to which variables, can depend on the input data.

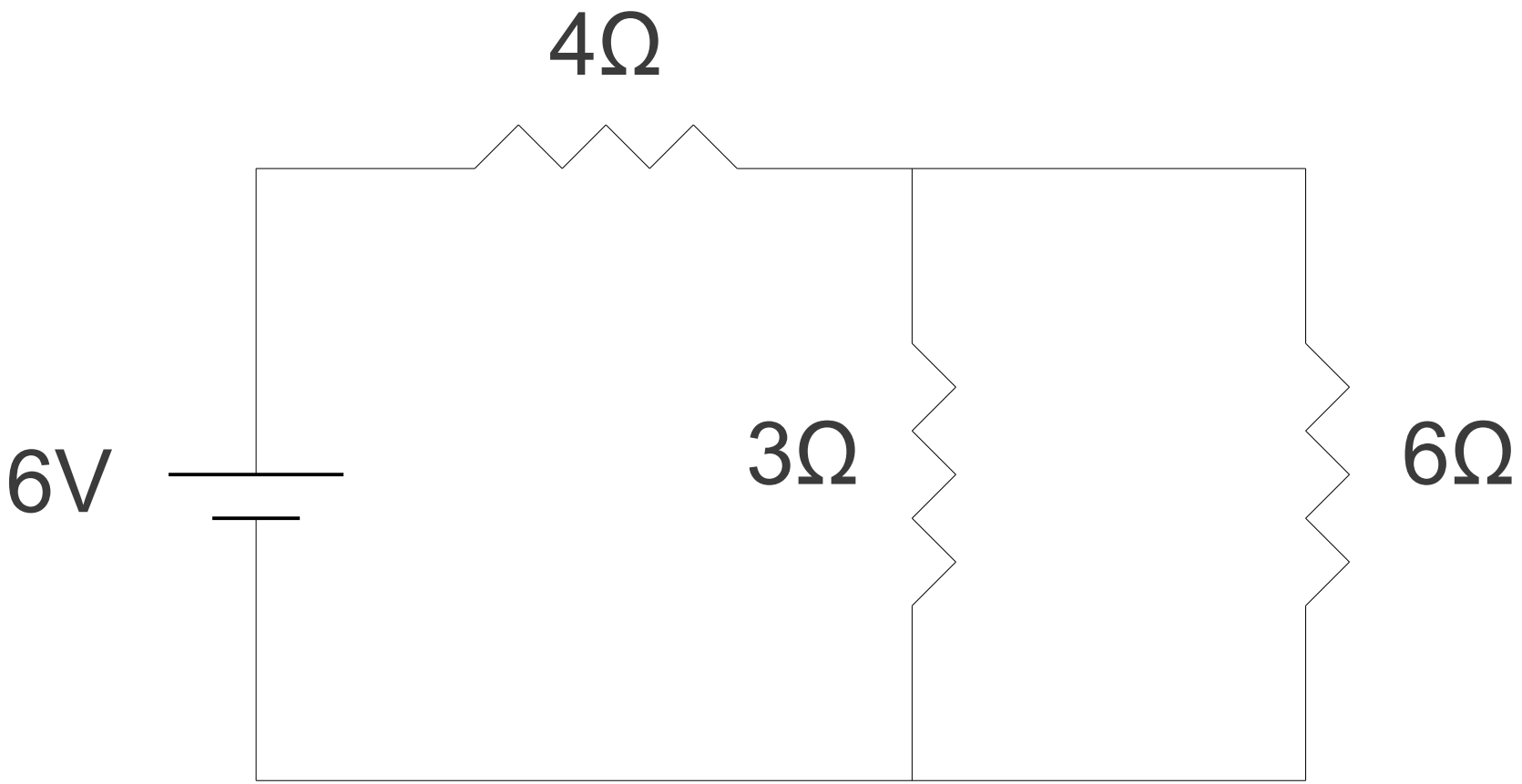
A Hybrid Approach

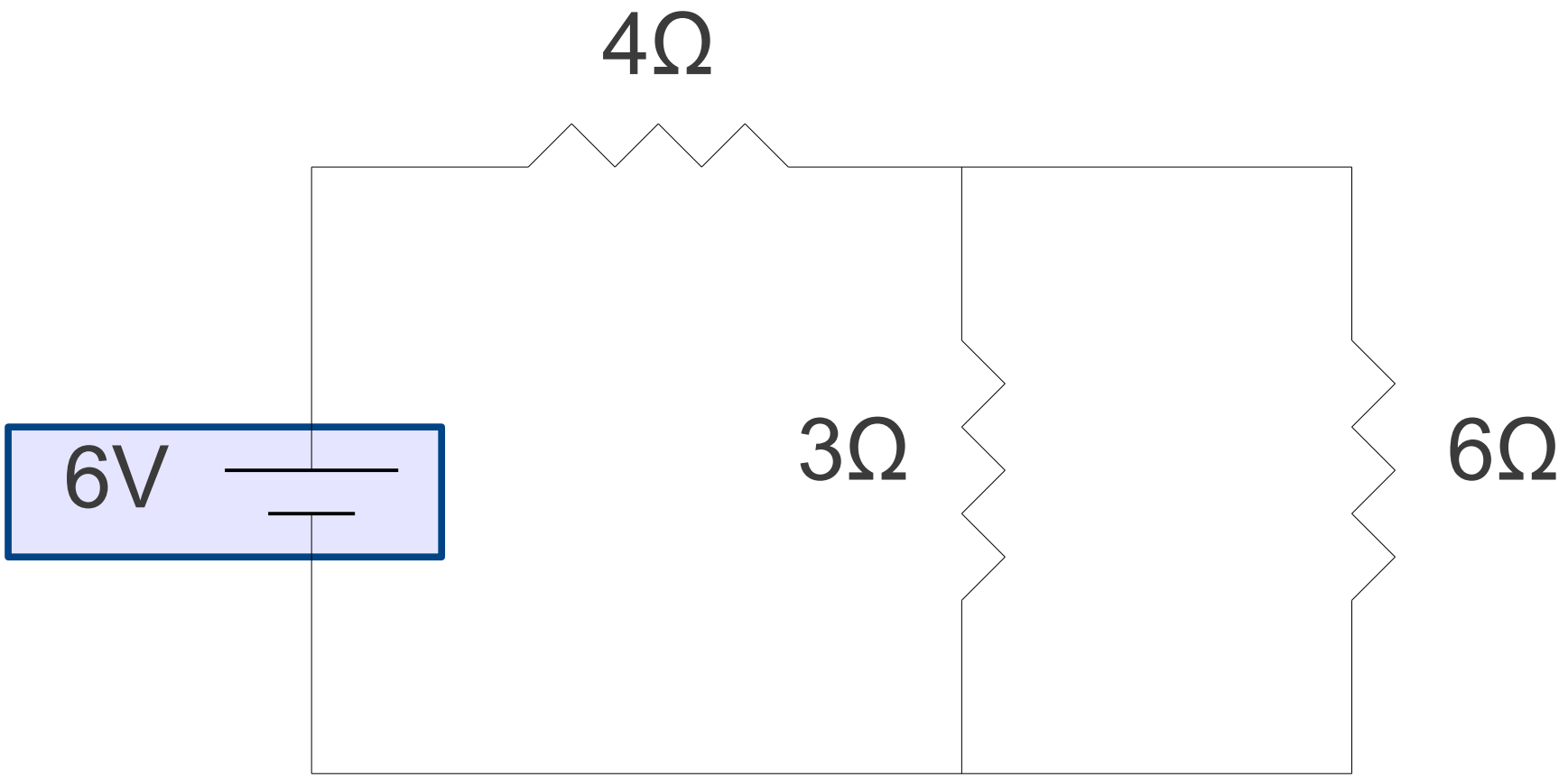


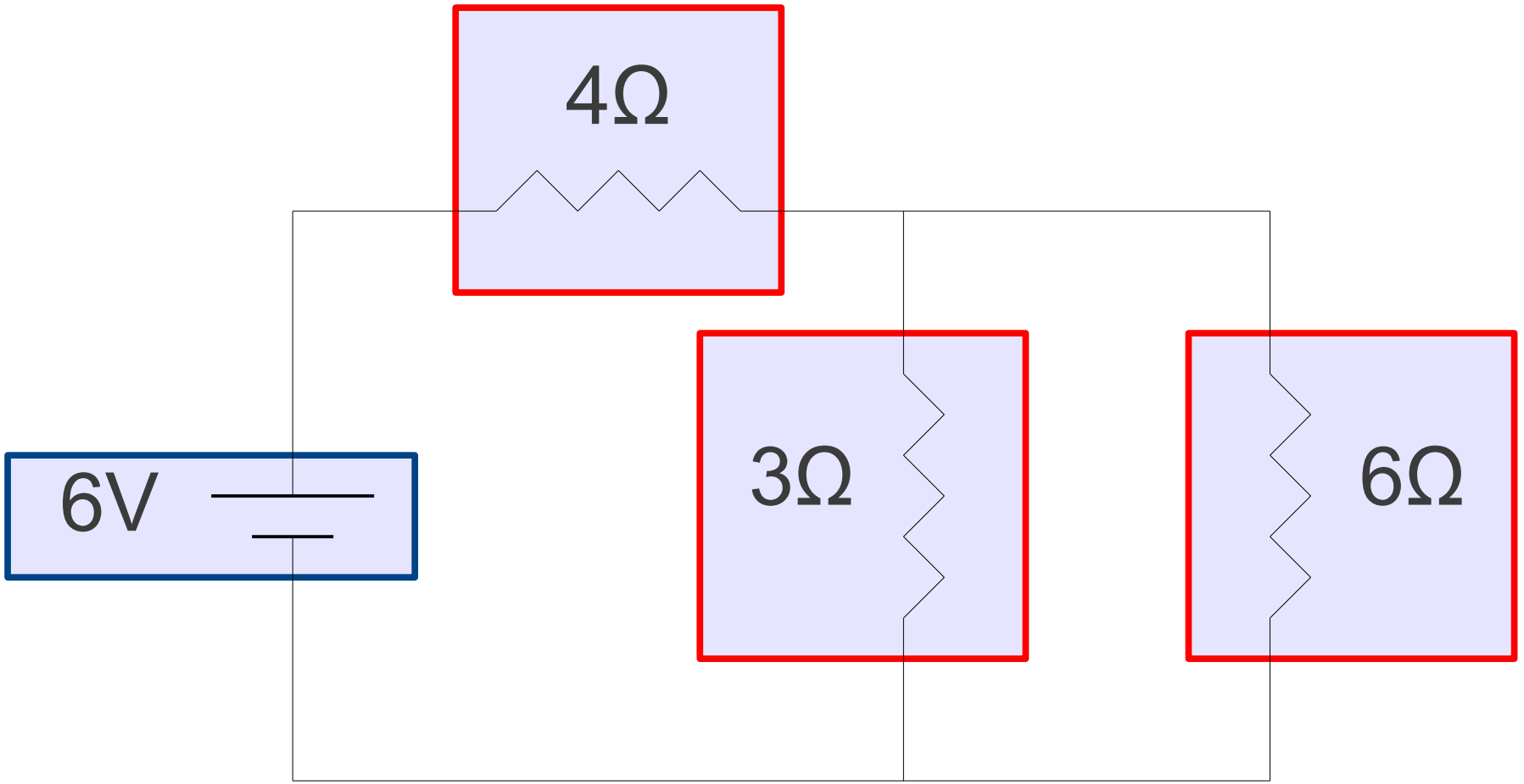
Hybrid Approach

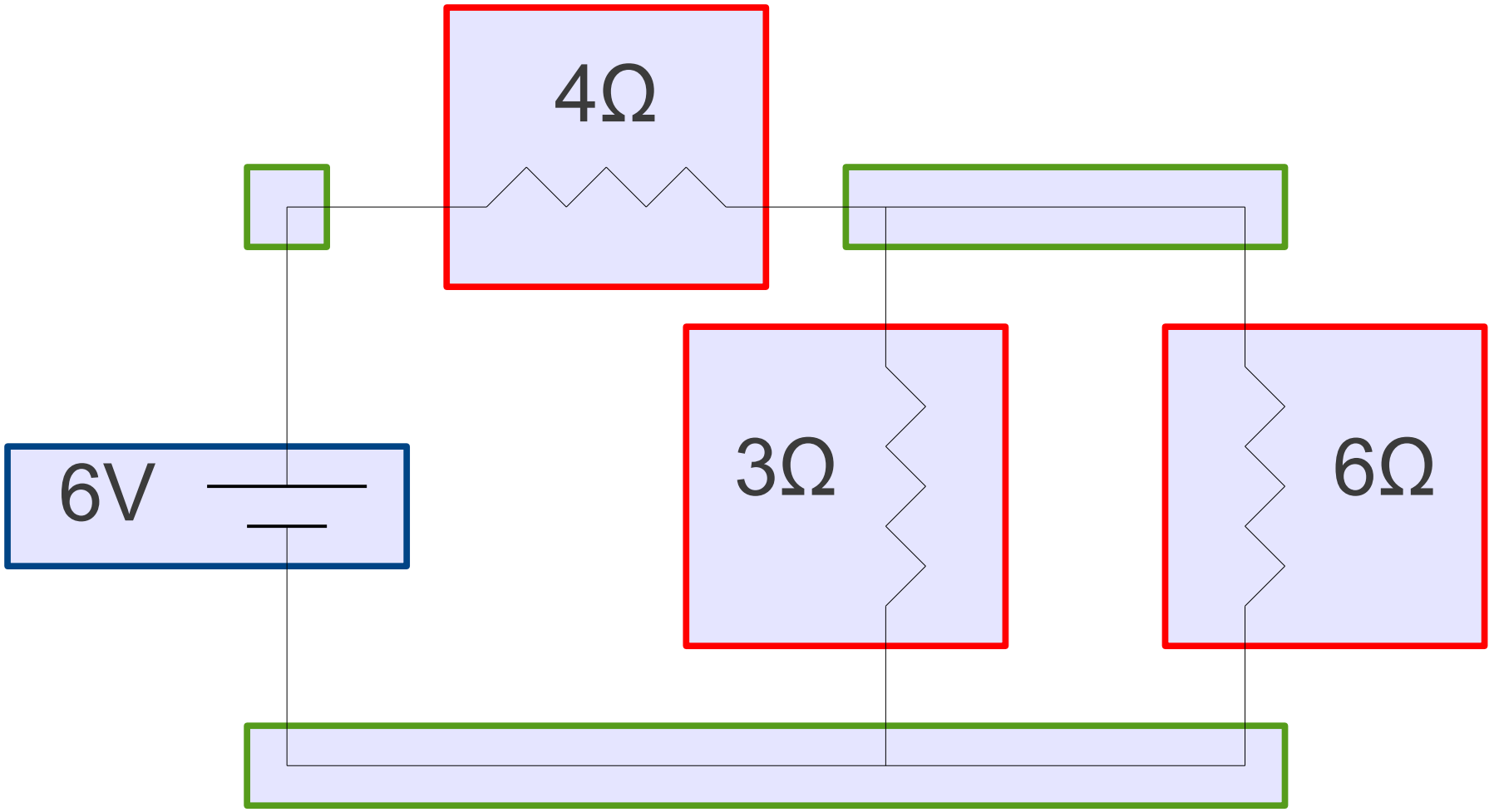


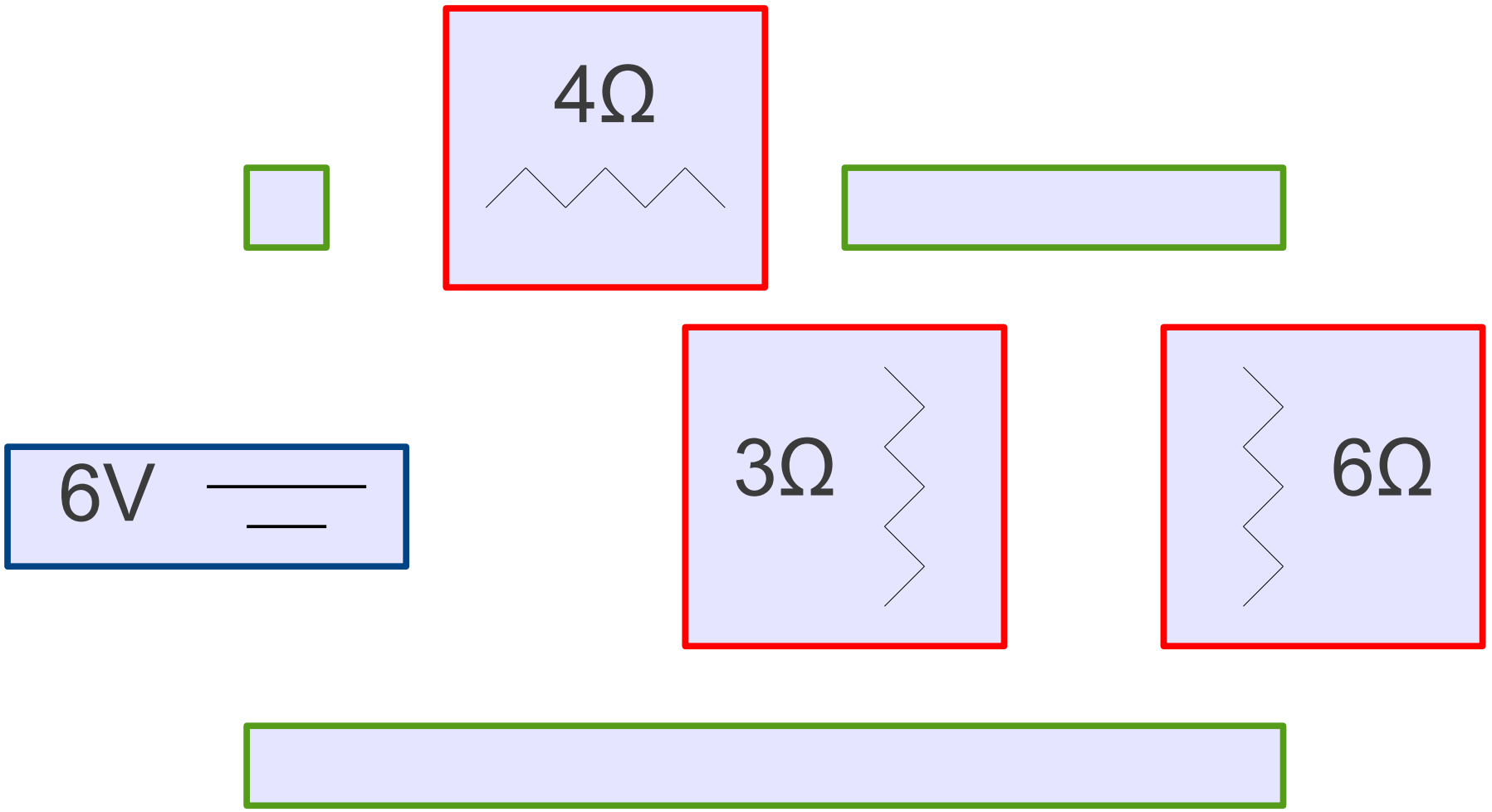
How does a compiler work?

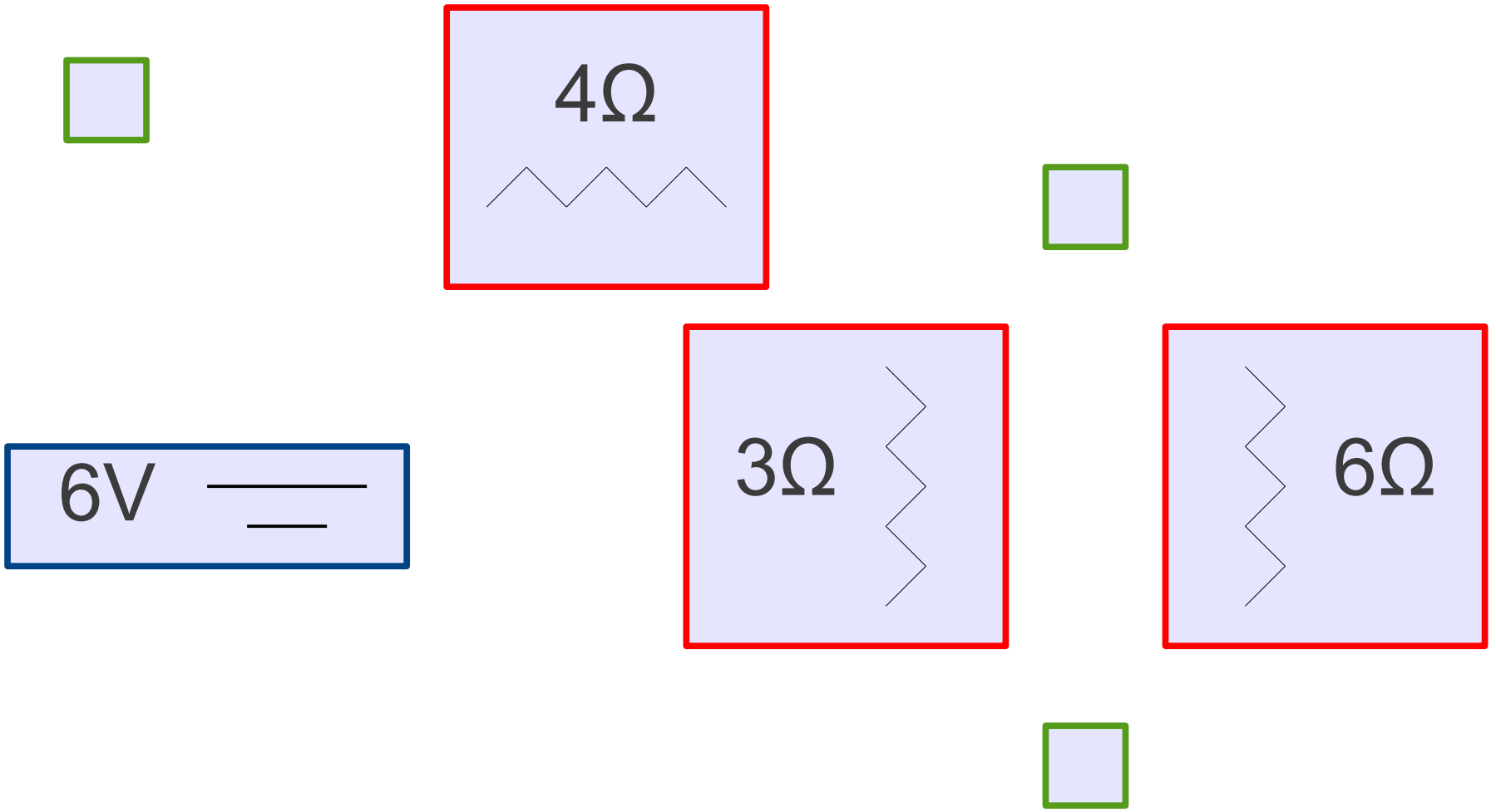

4Ω
6V
3Ω
6Ω

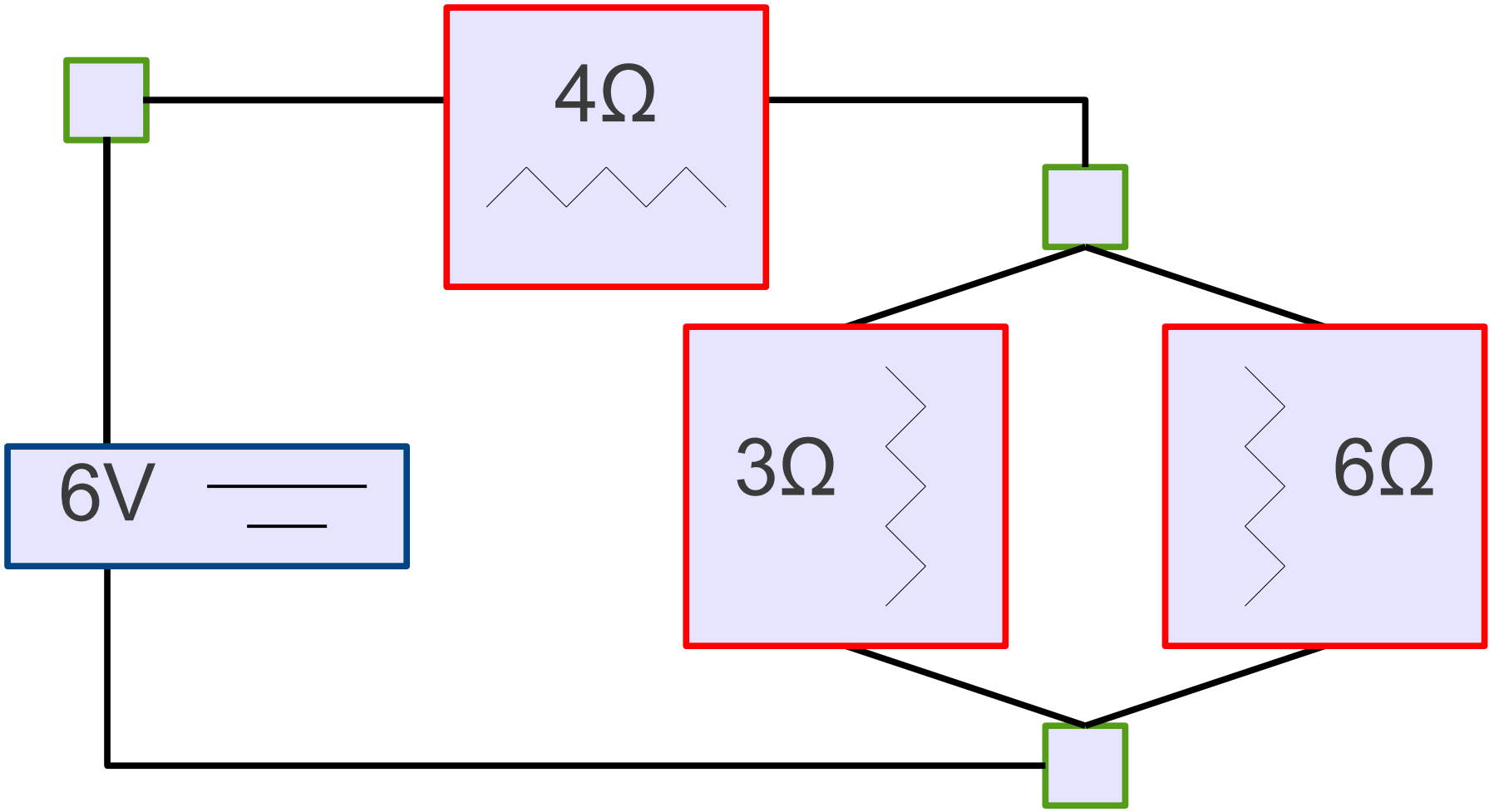

4Ω
6V
3Ω
6Ω

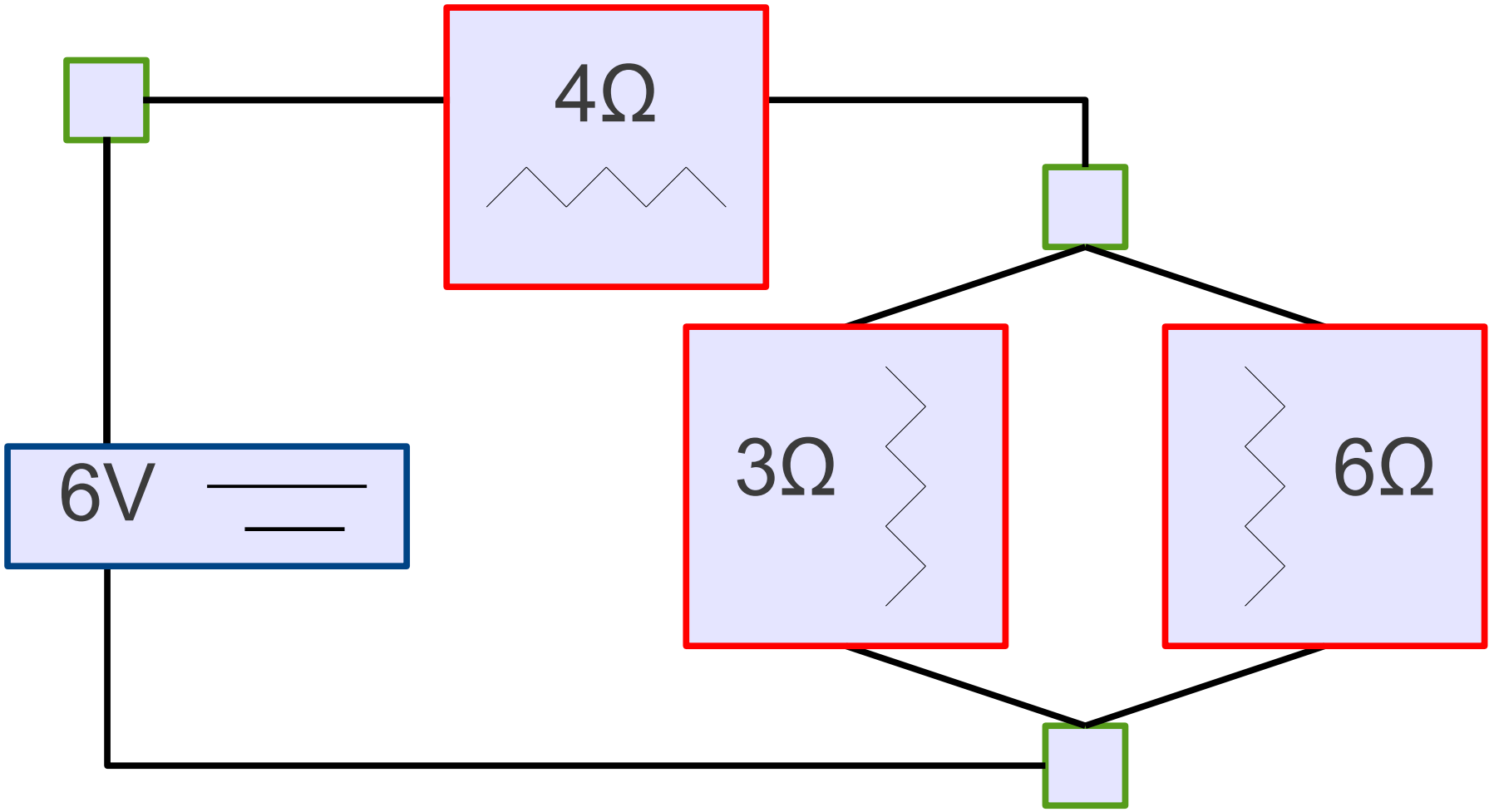

4Ω
3Ω
6Ω
6V


4Ω
3Ω
6Ω
6V

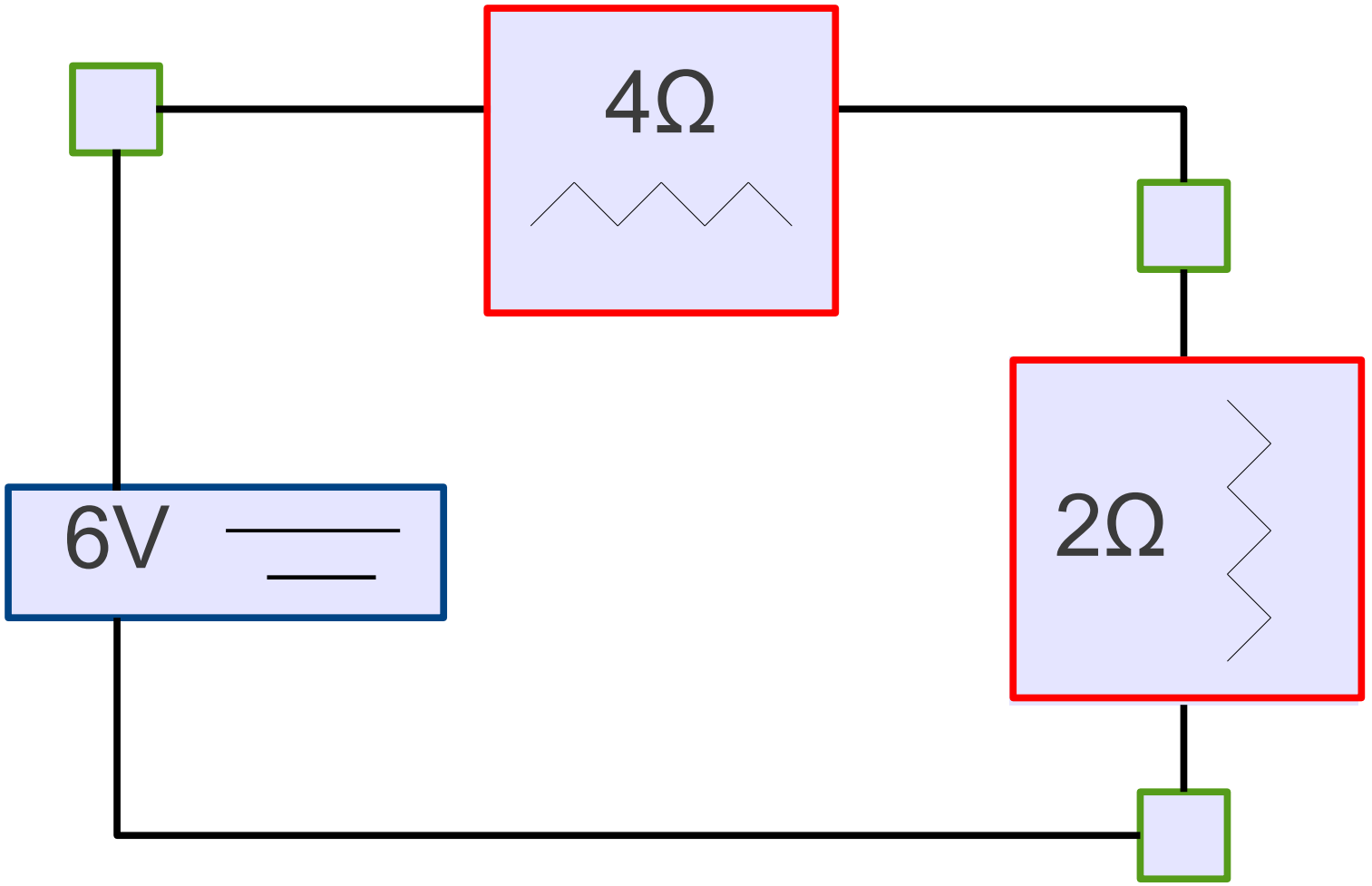

4Ω
6V
3Ω
6Ω


4Ω
6V
3Ω
6Ω


4Ω
3Ω
6Ω
6V



$$\frac{1}{\frac{1}{3\,\Omega}+\frac{1}{6\,\Omega}}=2\ \Omega$$



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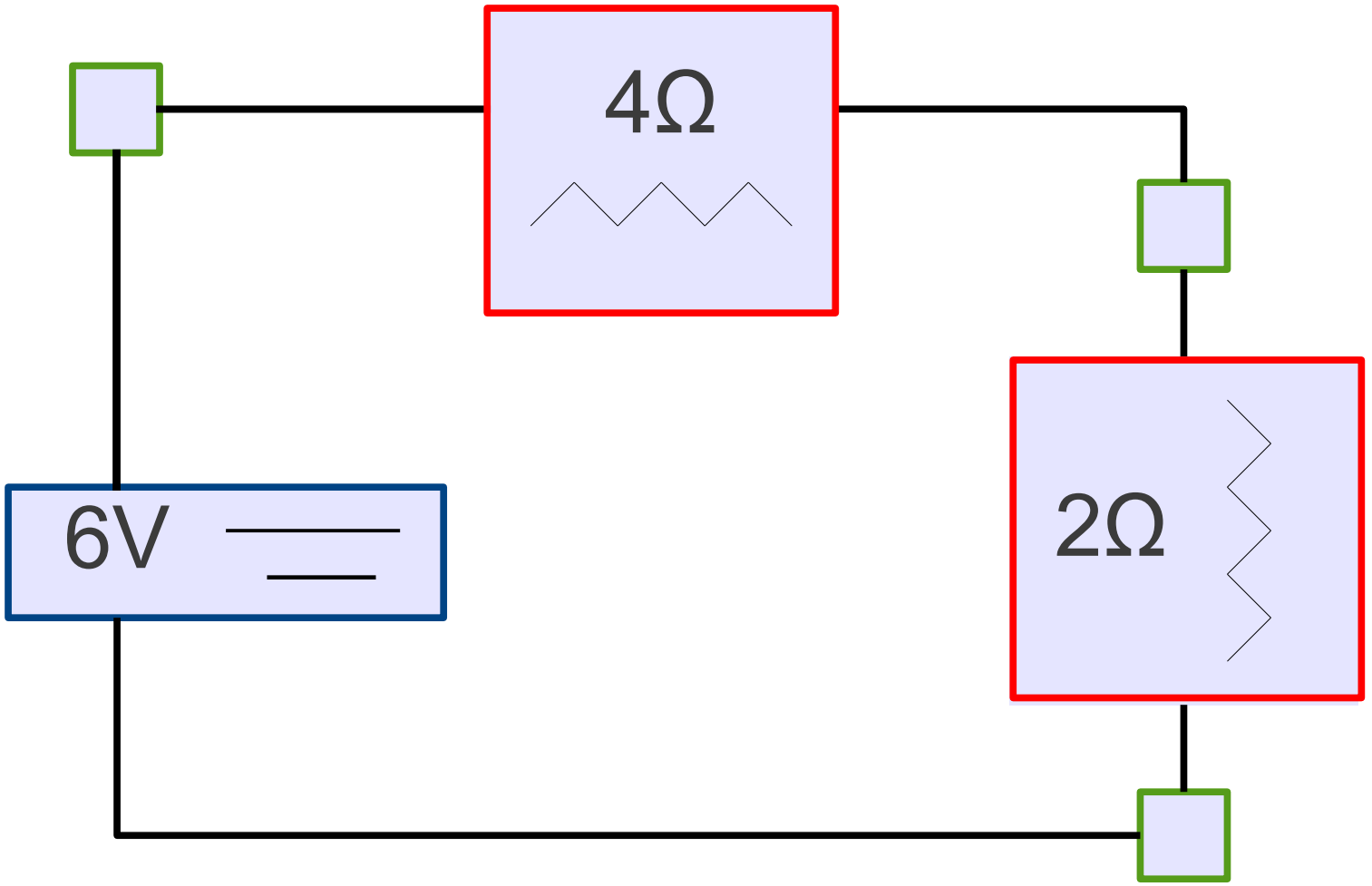
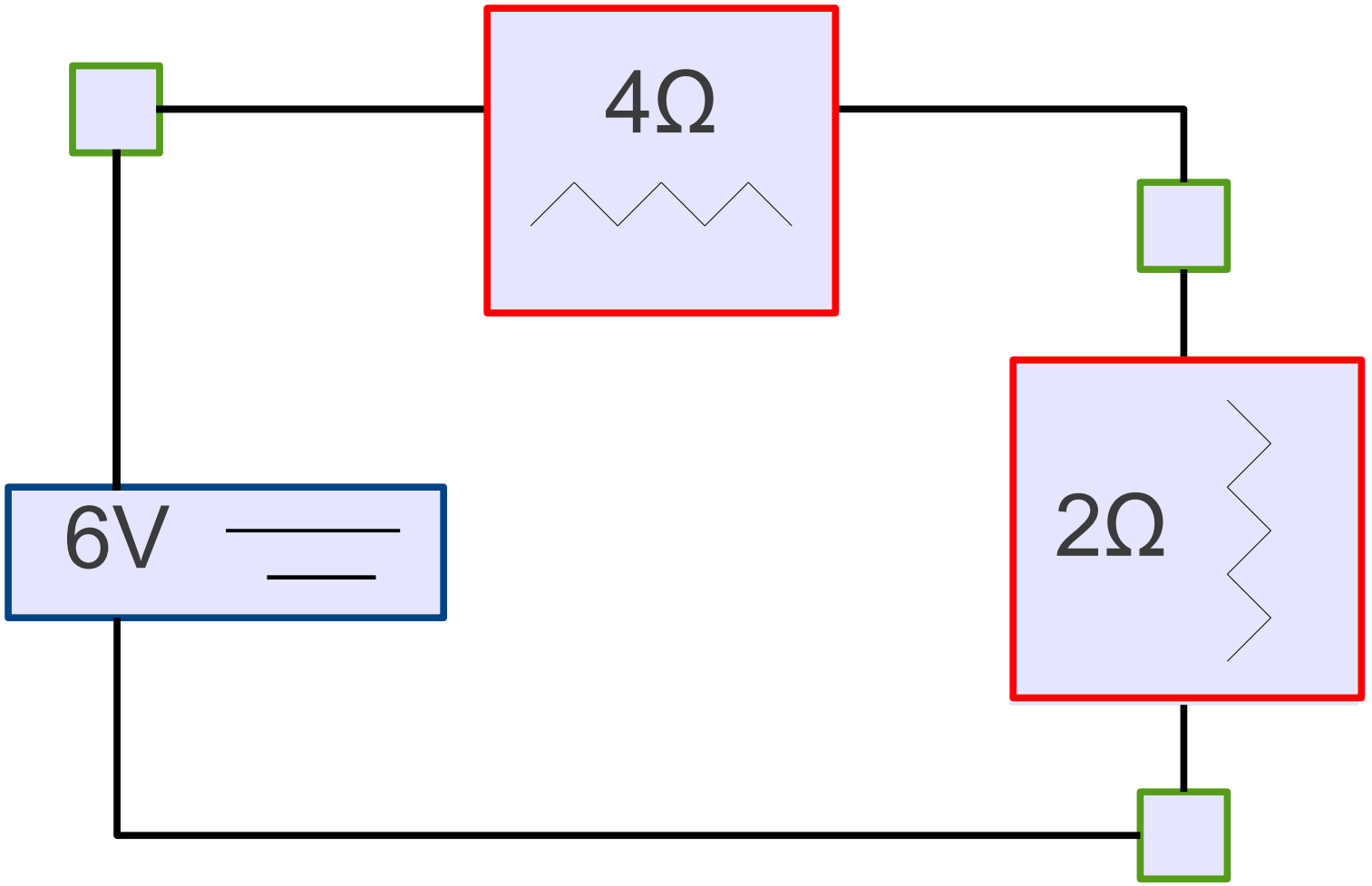
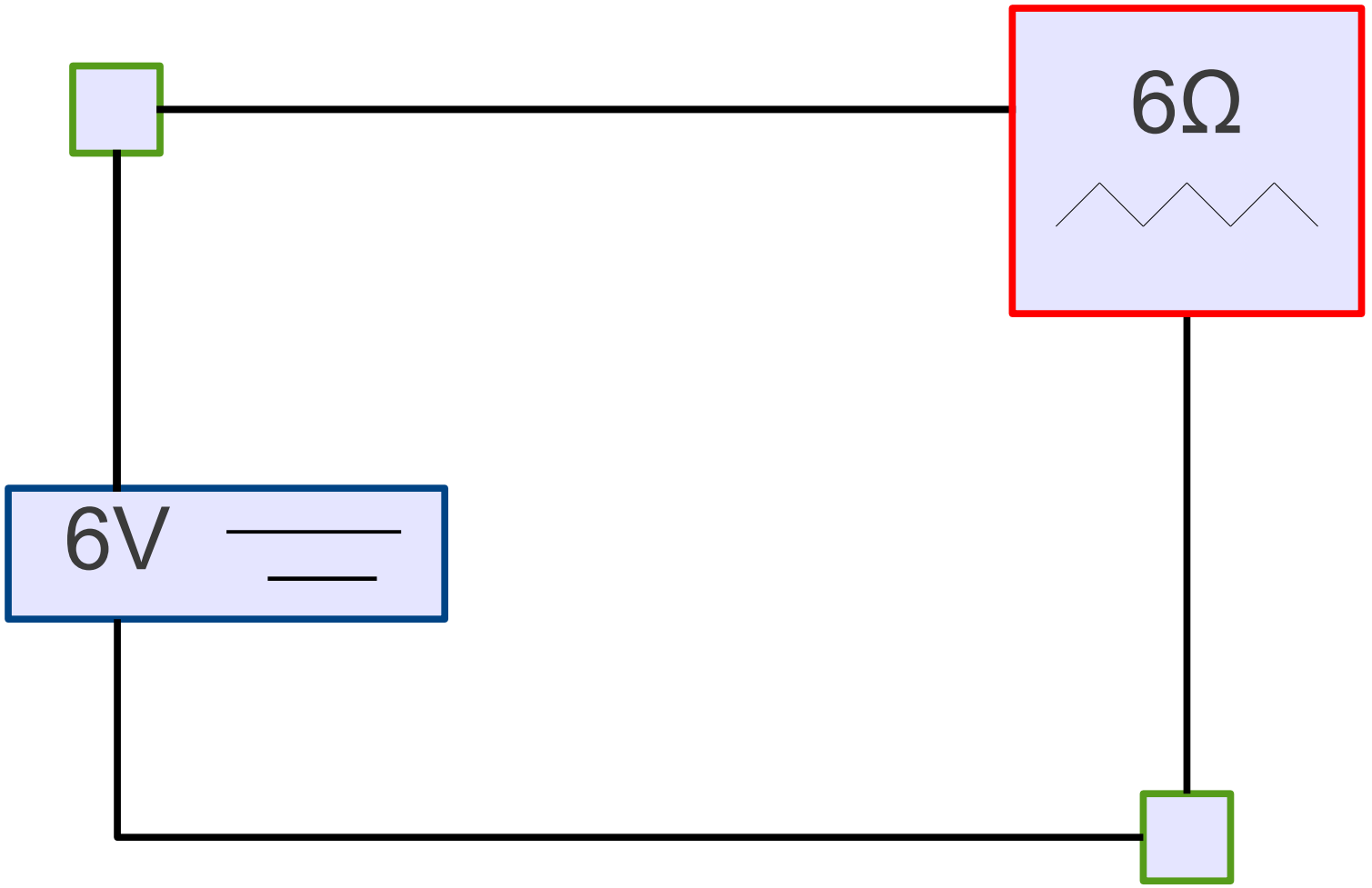

4Ω
6V
2Ω



$$4\,\Omega + 2\,\Omega = 6\,\Omega$$



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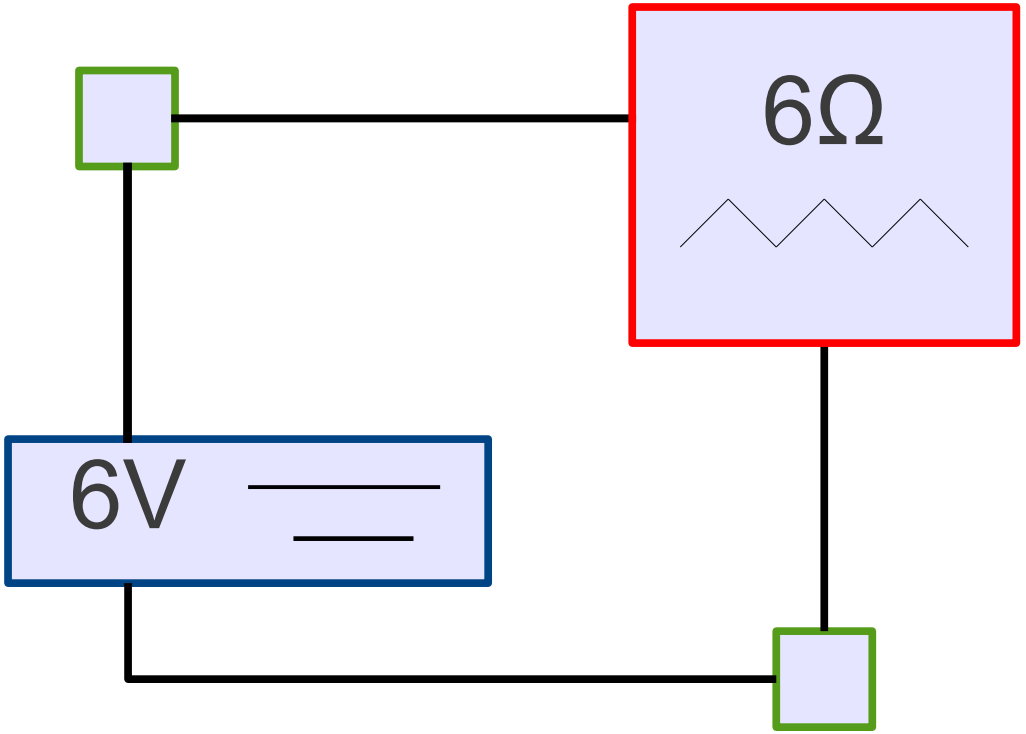
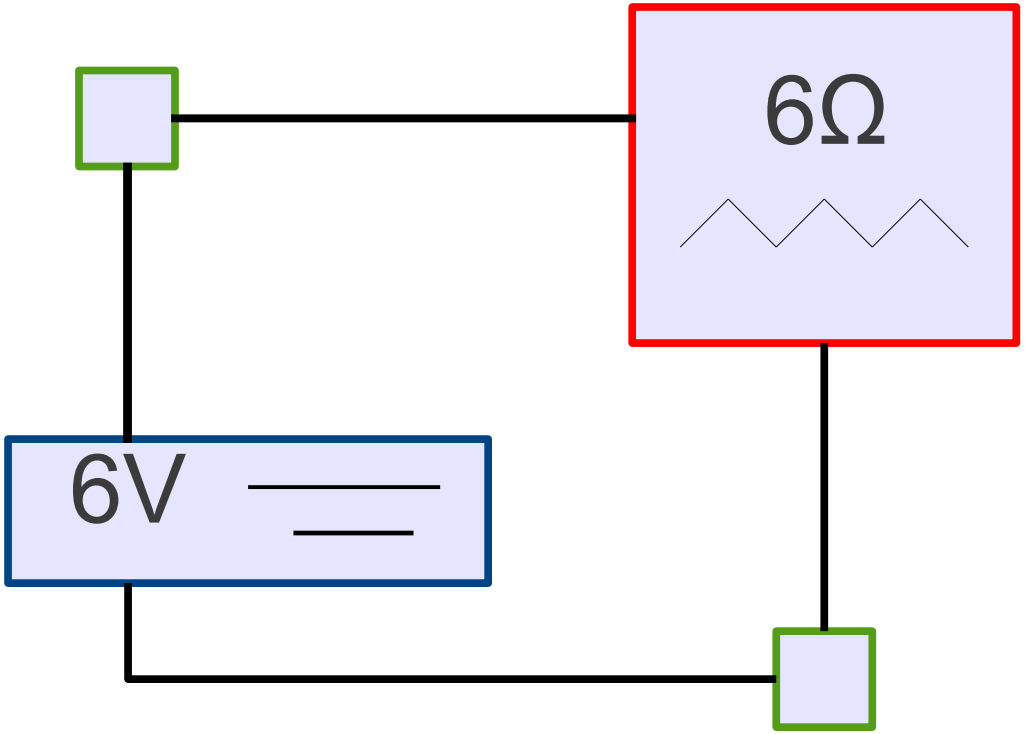
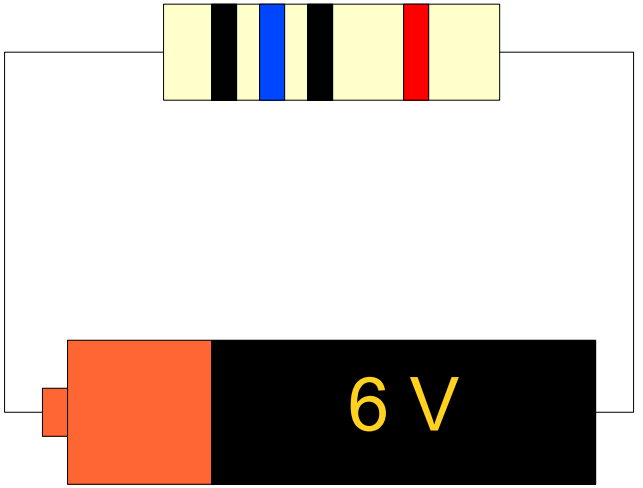
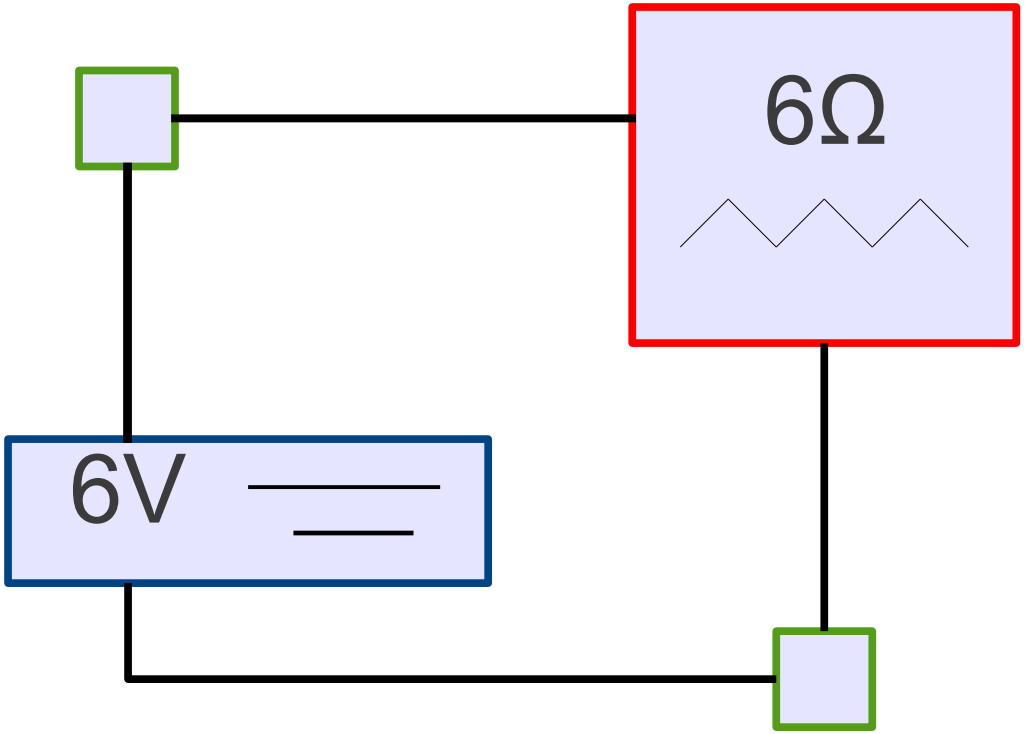
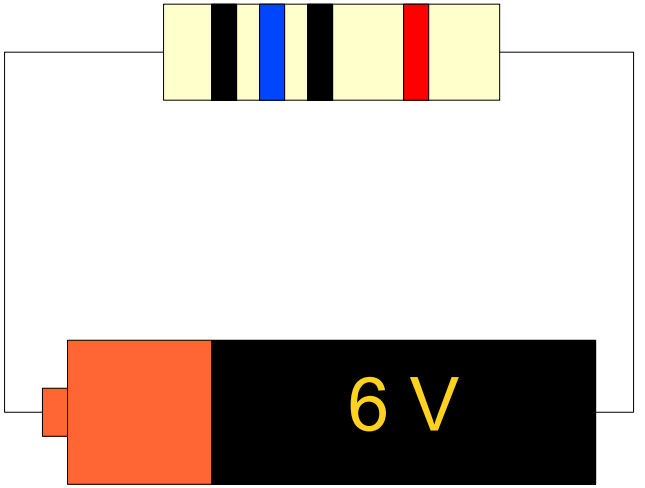

6Ω
6V

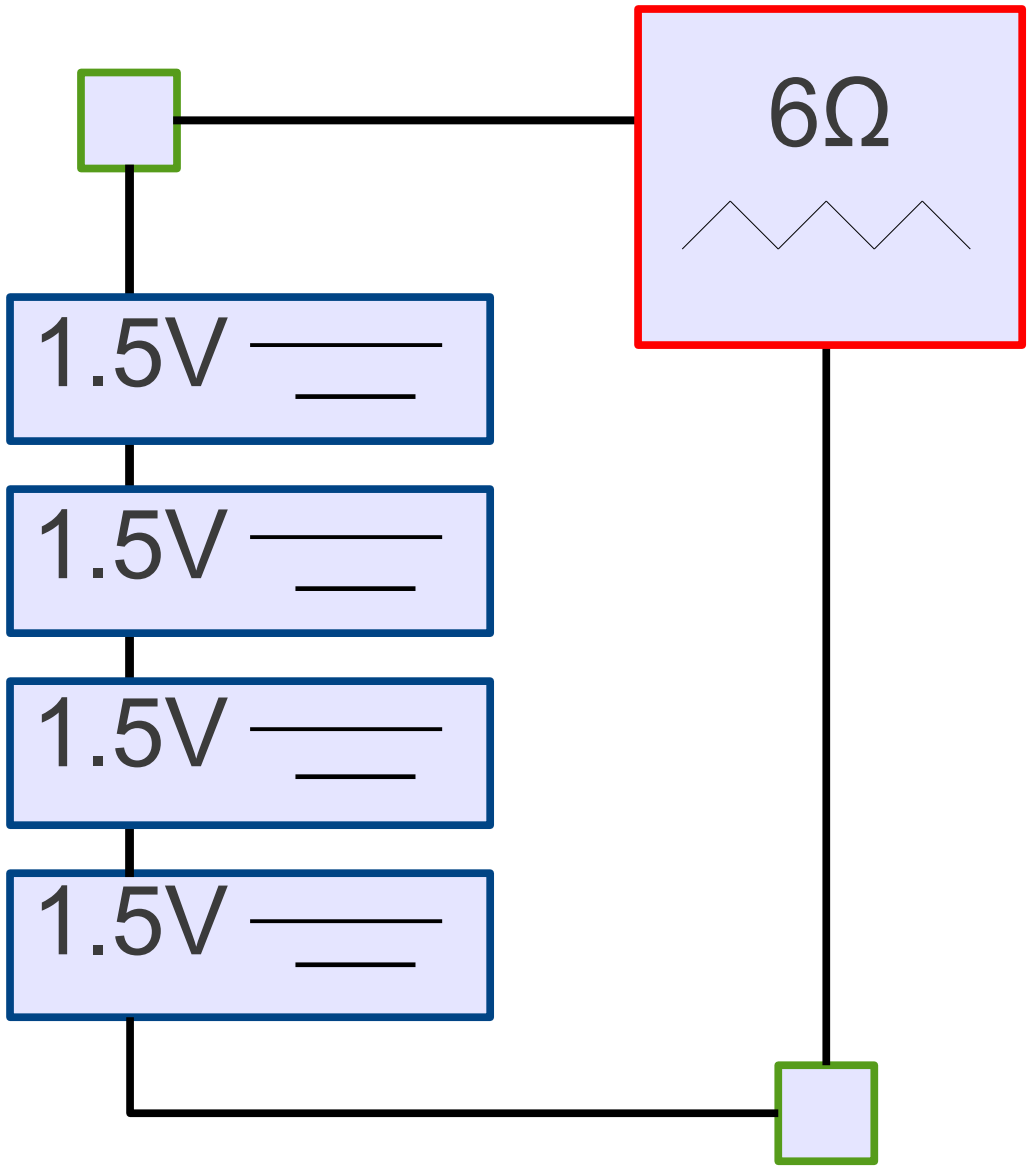

6Ω
6V

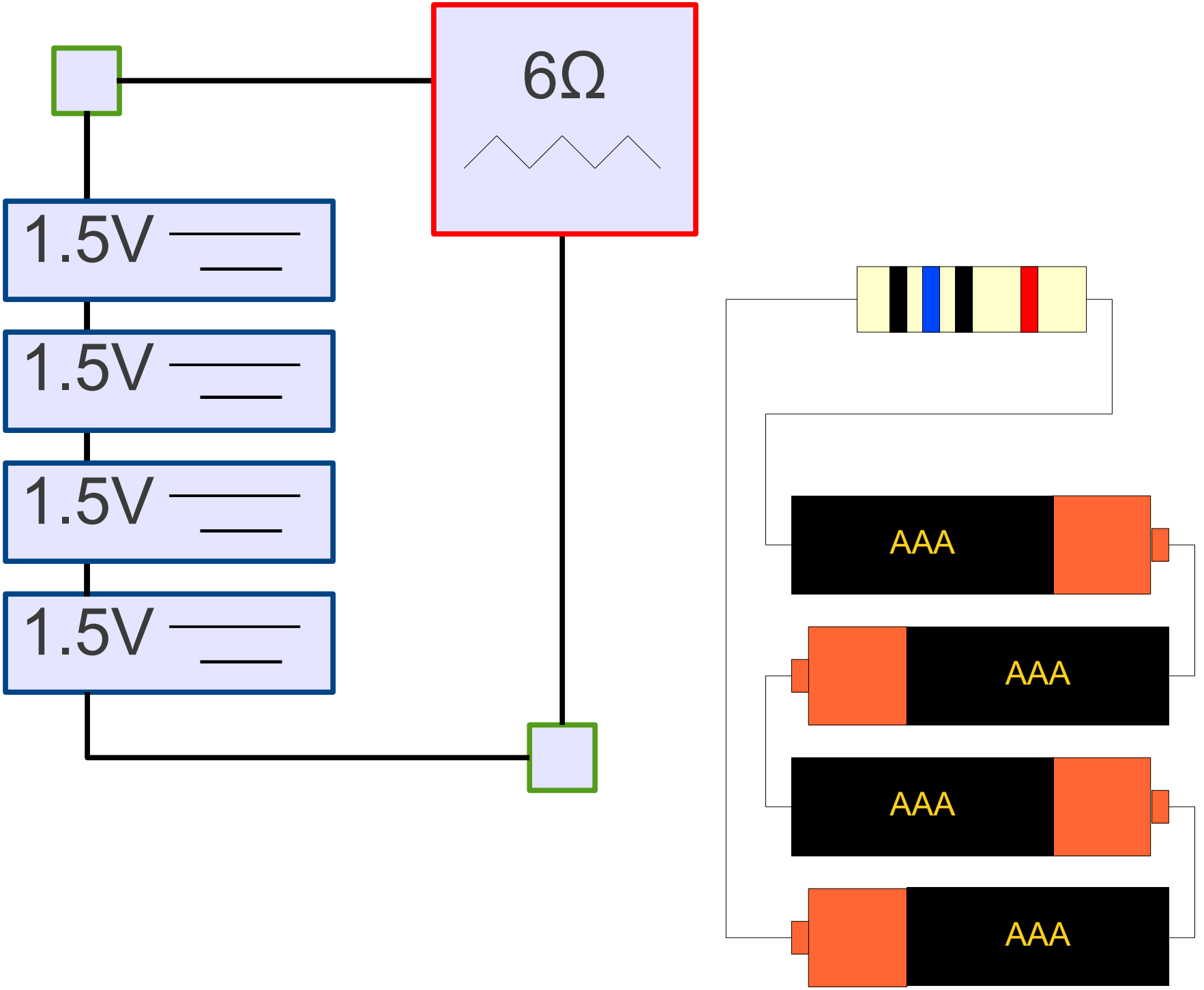

6 V

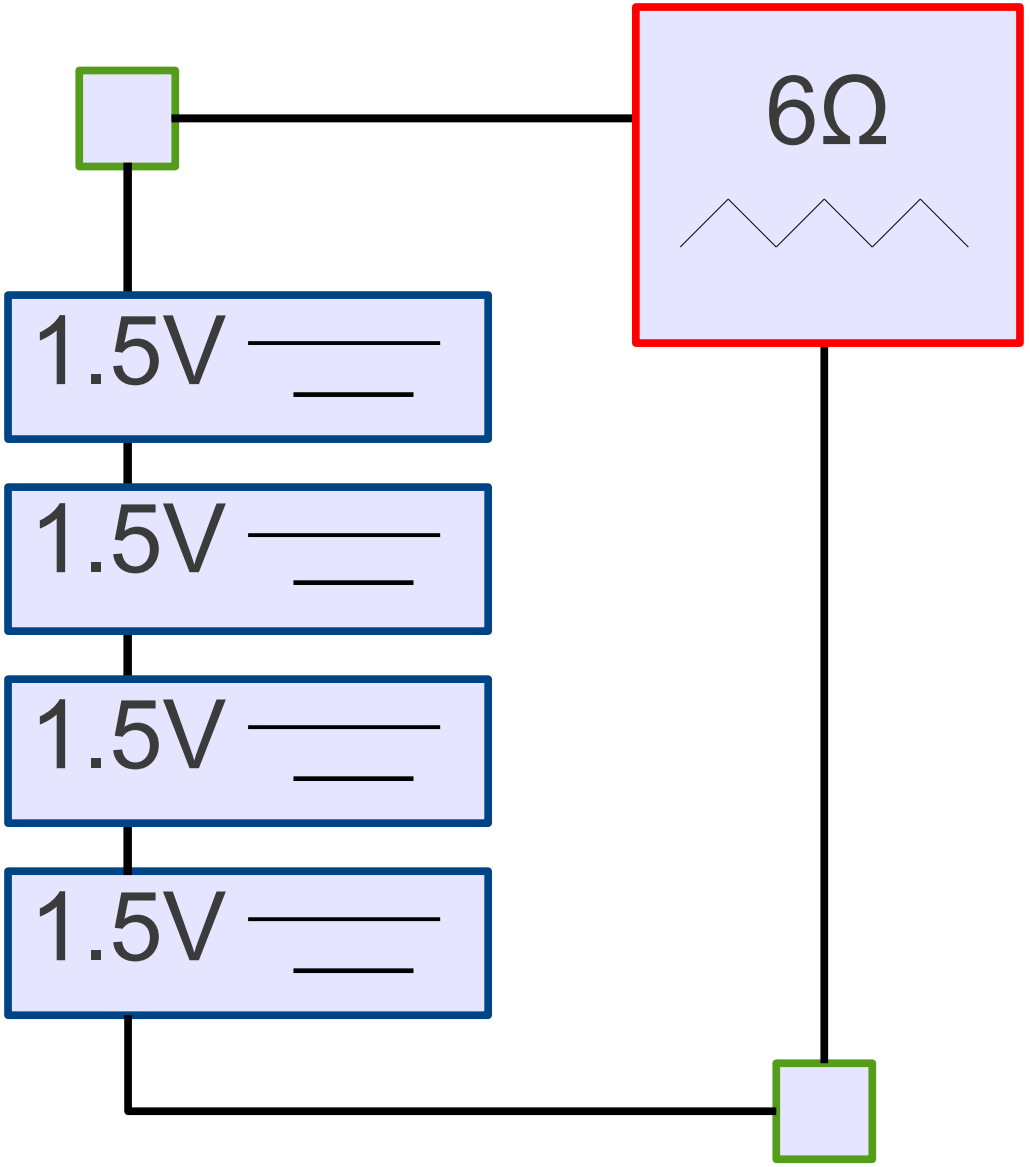


Total Cost: $4.75

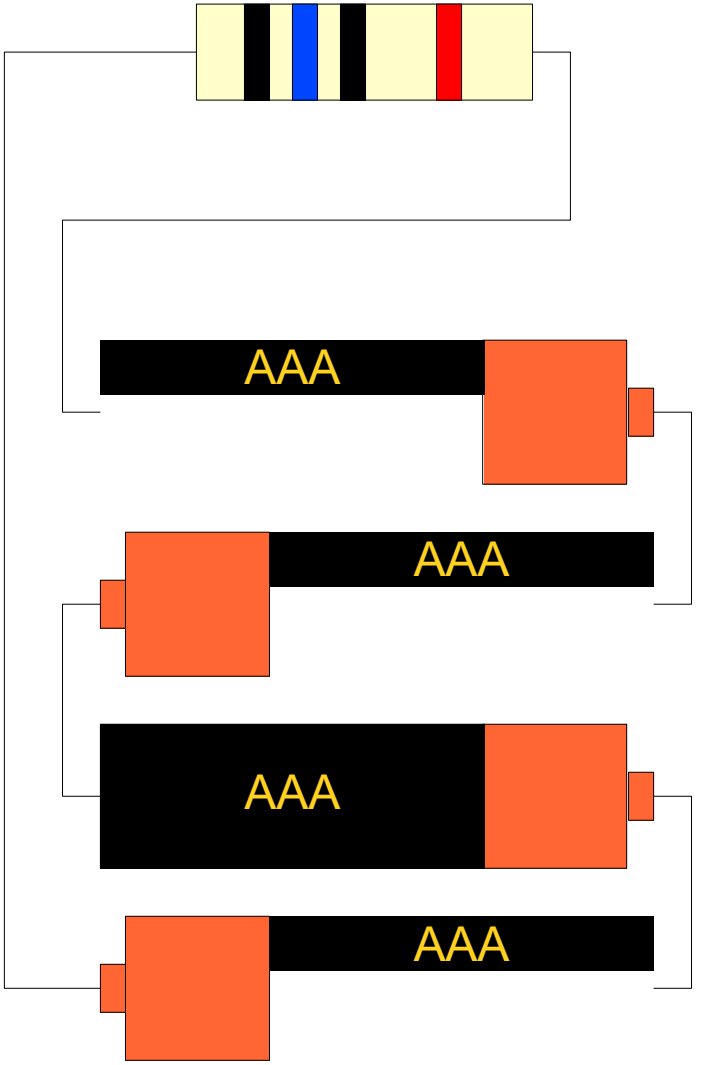



6Ω
1.5V
1.5V
1.5V
1.5V


6Ω
1.5V
1.5V
1.5V
1.5V
AAA
AAA
AAA
AAA



Total Cost: $1.00



From Description to Implementation

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- **Lexical analysis (Scanning):** Identify logical pieces of the description.

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- **Lexical analysis (Scanning):** Identify logical pieces of the description.
- **Syntax analysis (Parsing):** Identify how those pieces relate to each other.
- **Semantic analysis:** Identify the meaning of the overall structure.

From Description to Implementation

- **Lexical analysis (Scanning):** Identify logical pieces of the description.
- **Syntax analysis (Parsing):** Identify how those pieces relate to each other.
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- **Optimization:** Improve the resulting structure.

Lexical Analysis

- First step: recognize words.
  - Smallest unit above letters

This is a sentence.

- Lexical analysis is not trivial. Consider:

ist his ase nte nce

Real world Example: Watch it On YouTube!

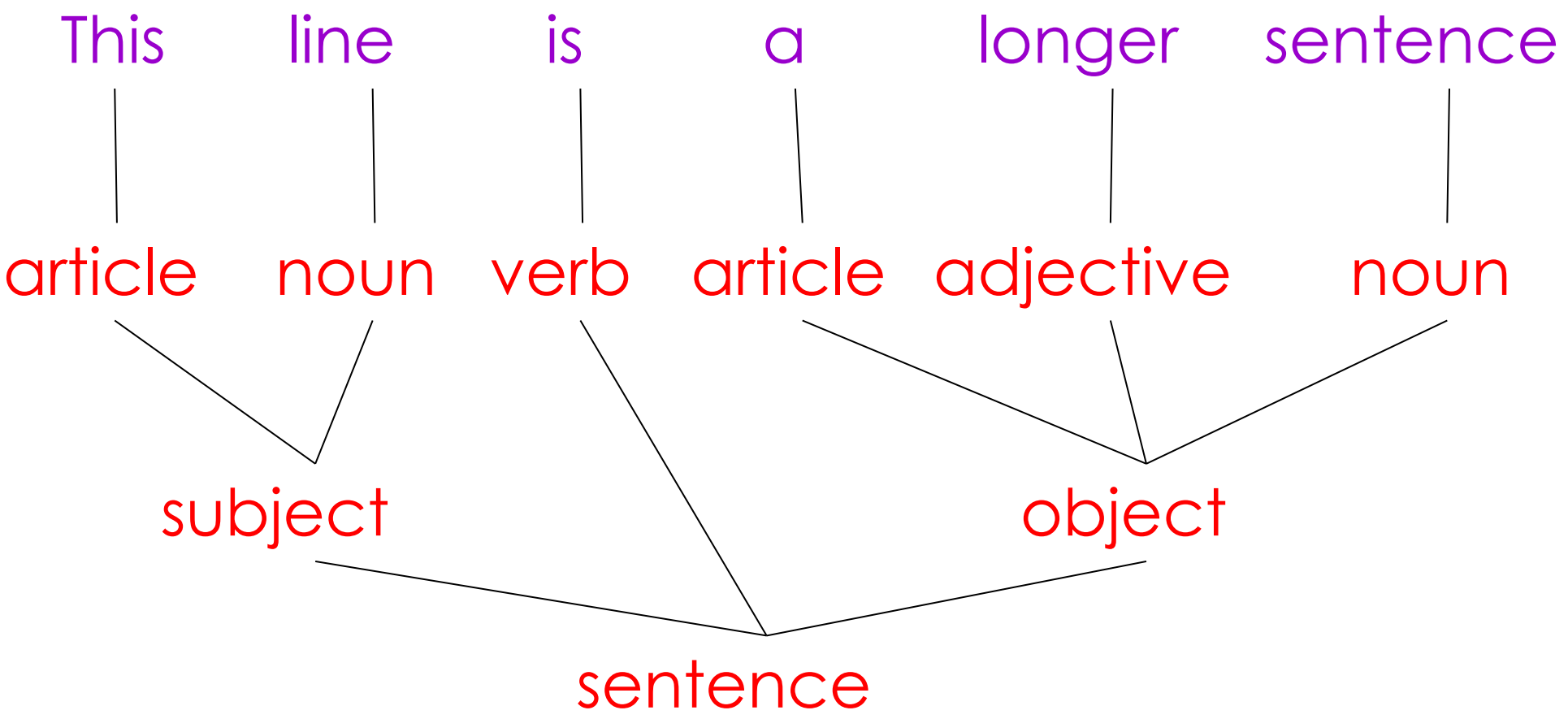
- Lexical analyzer divides program text into "words" or "tokens"

  If x == y then z = 1; else z = 2;

- Units:

- Once words are understood, the next step is to understand sentence structure

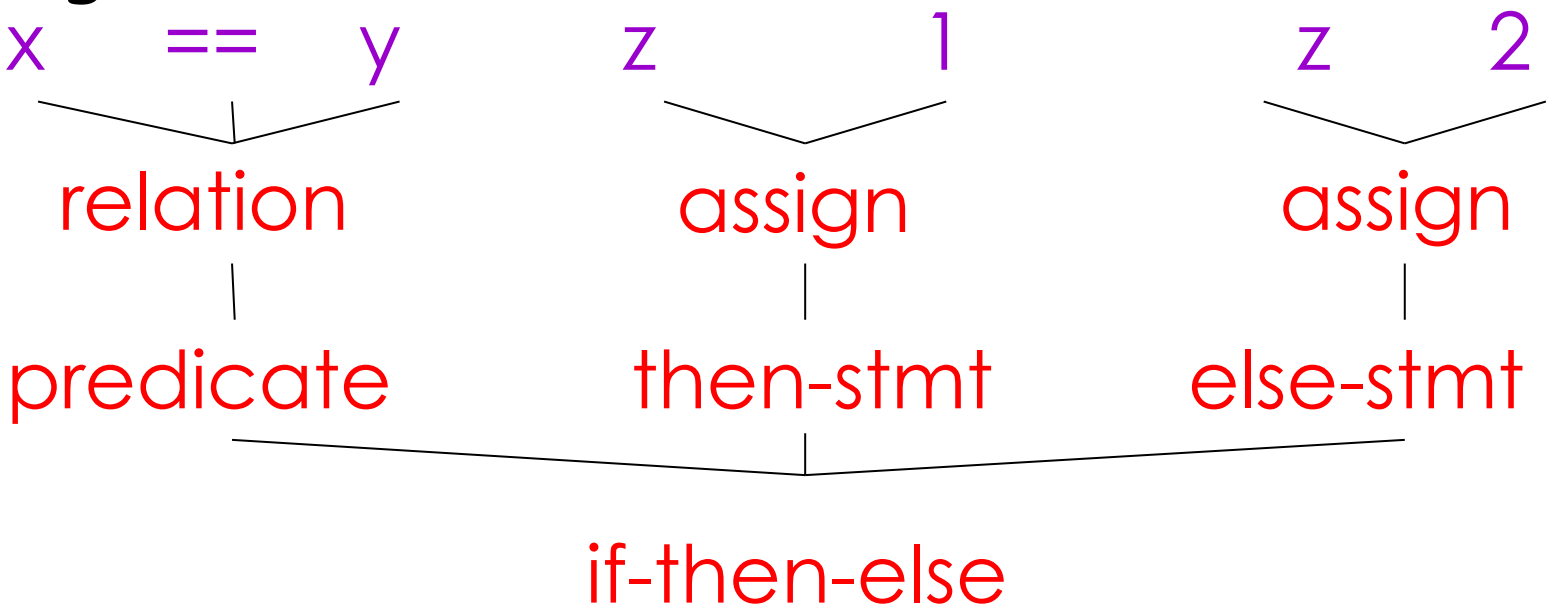
- Parsing = Diagramming Sentences
  - The diagram is a tree


This
line
is
a
longer
sentence
article
noun
verb
article
adjective
noun
subject
object
sentence

- Parsing program expressions is the same
- Consider:

If x == y then z = 1; else z = 2;

- Diagrammed:



- Once sentence structure is understood, we can try to understand “meaning”
  - But meaning is too hard for compilers
- Compilers perform limited semantic analysis to catch inconsistencies

Semantic Analysis in English

- Example:

  Jack said Jerry left his assignment at home.

  What does "his" refer to? Jack or Jerry?

- Even worse:

  Jack said Jack left his assignment at home?

  How many Jacks are there?

  Which one left the assignment?

Semantic Analysis in Programming

- Programming languages define strict rules to avoid such ambiguities
- This C++ code prints "4"; the inner definition is used

```
{
    int Jack = 3;
    {
        int Jack = 4;
        cout << Jack;
    }
}
```

More Semantic Analysis

- Compilers perform many semantic checks besides variable bindings

- Example:

  Jack left her homework at home.

- Possible type mismatch between her and Jack
  - If Jack is male

Optimization

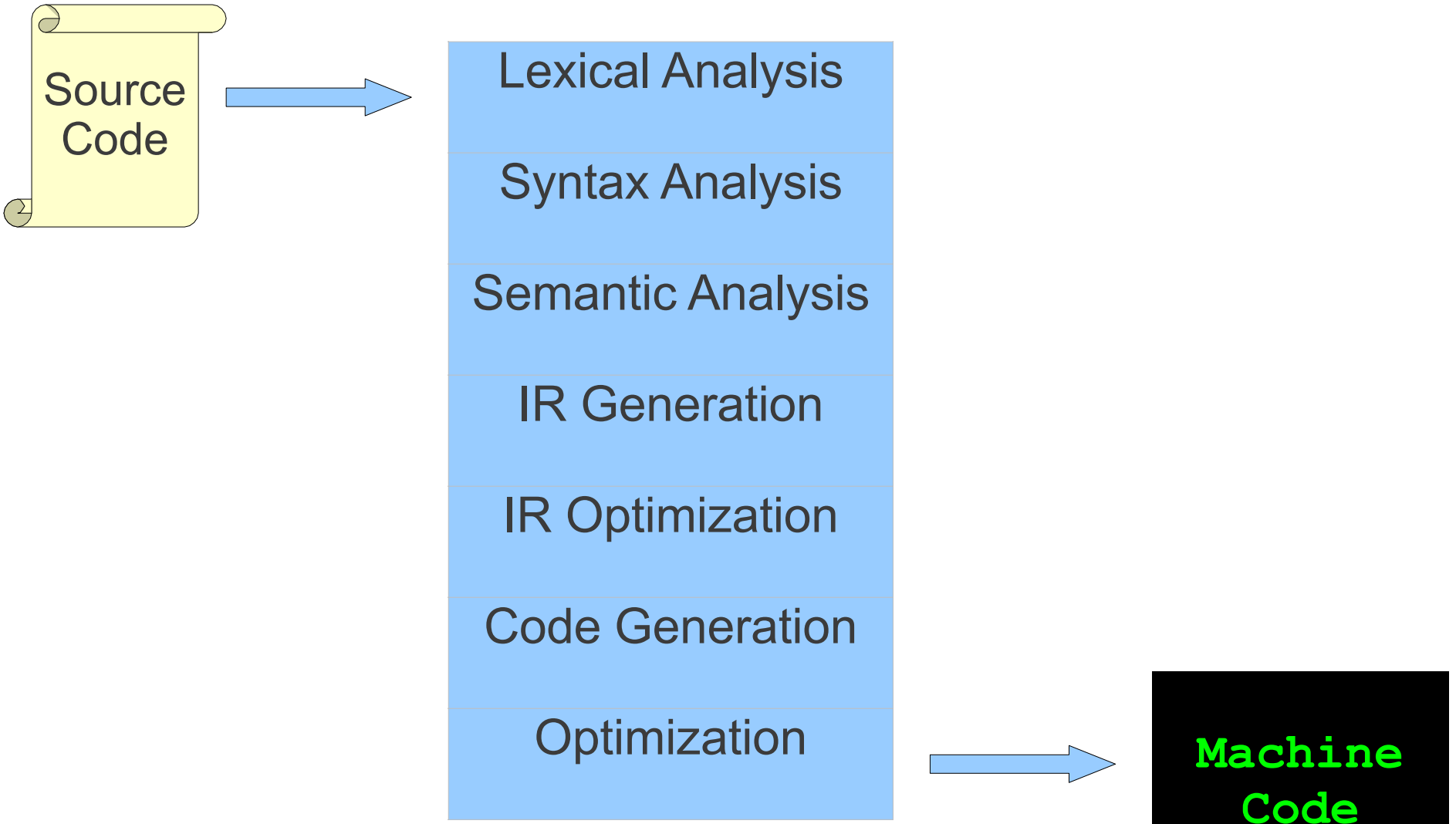
- No strong counterpart in English, but akin to editing

- Automatically modify programs so that they
  - Run faster
  - Use less memory
  - In general, to use or conserve some resource

Optimization Example

X = Y * 0 is the same as X = 0

(the * operator is annihilated by zero)


Source Code
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Semantic Analysis
IR Generation
IR Optimization
Code Generation
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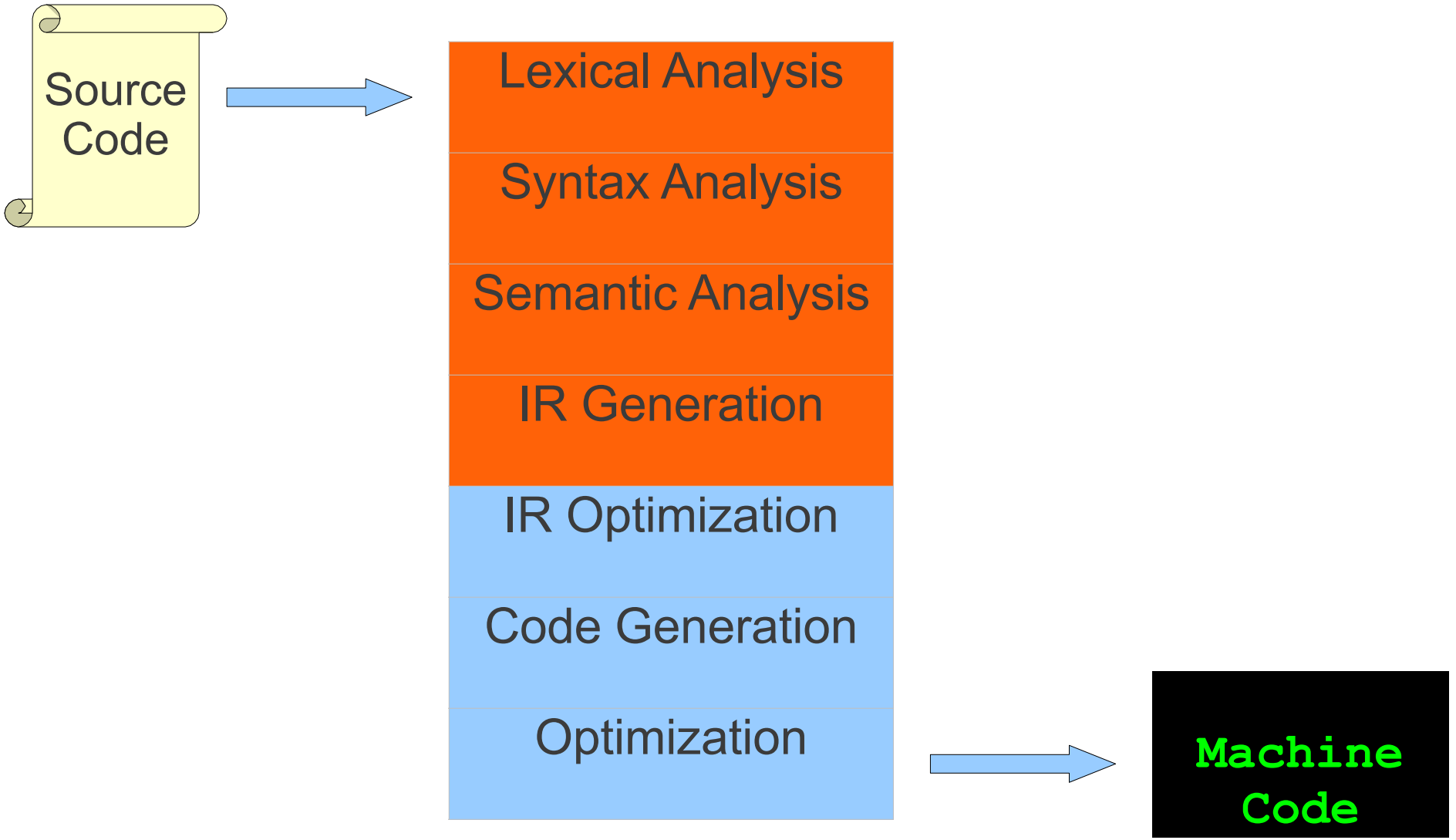
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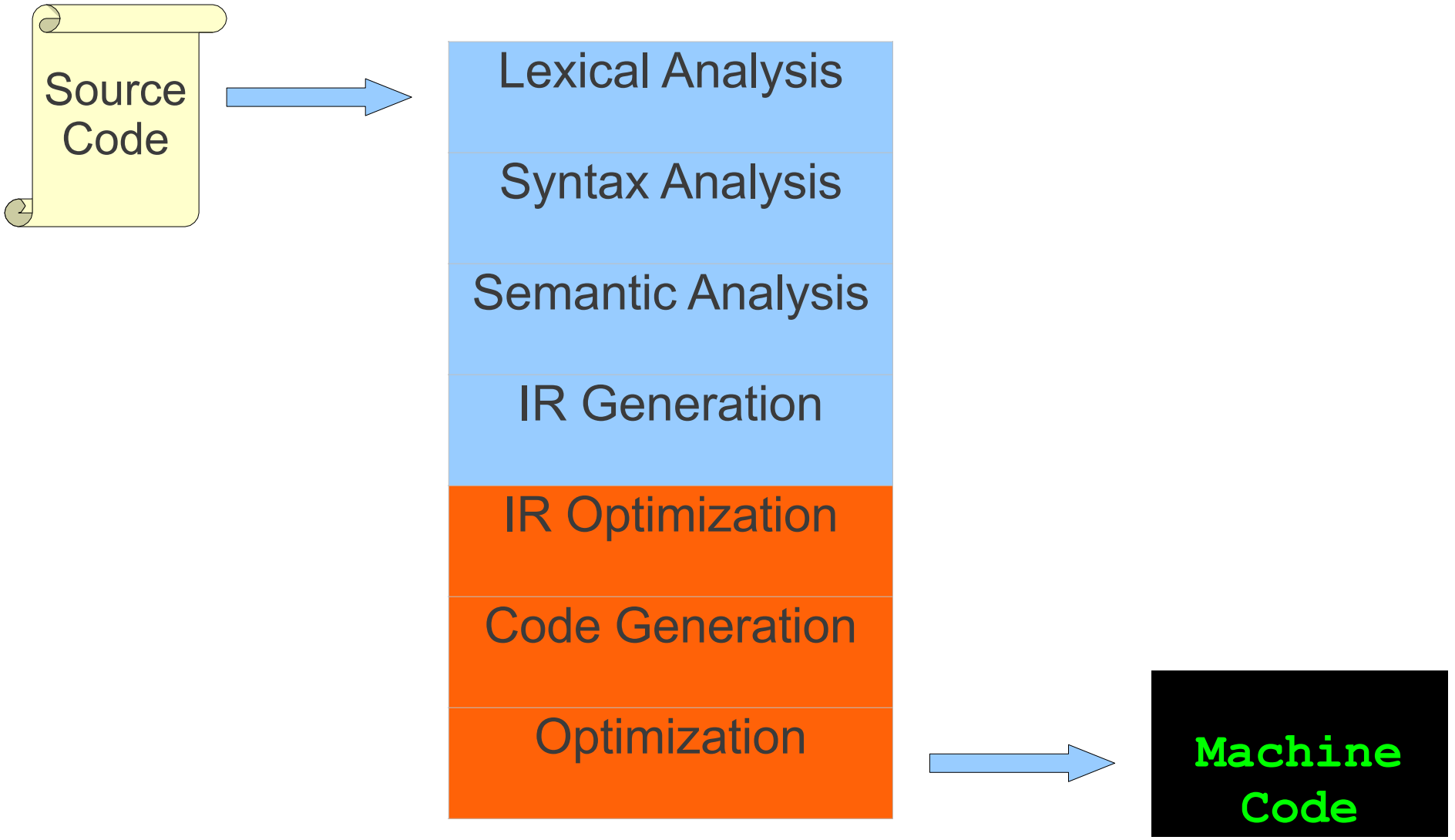
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while (y < z) {
  int x = a + b;
  y += x;
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T_Identifier z
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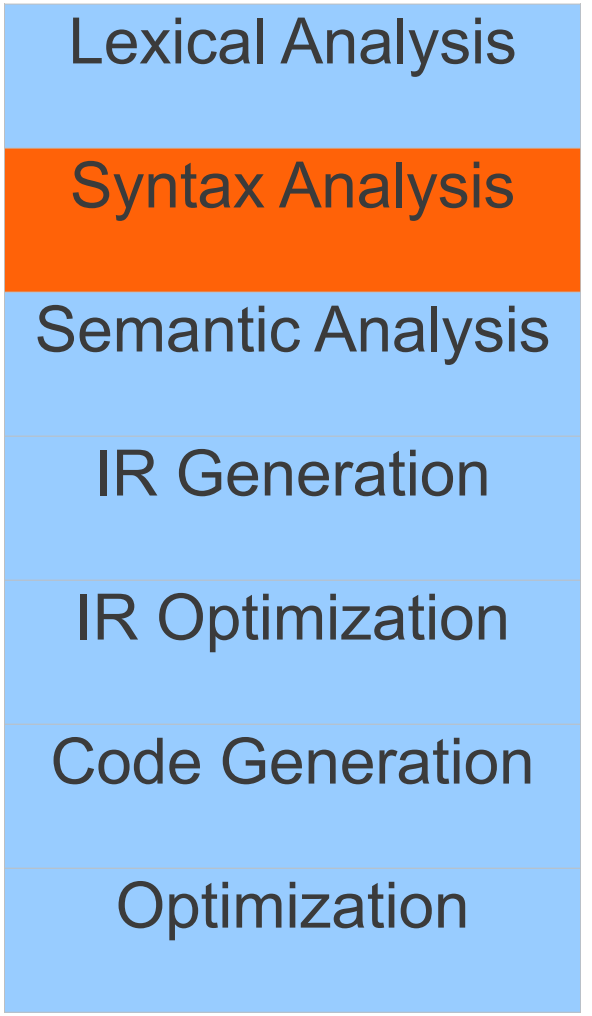

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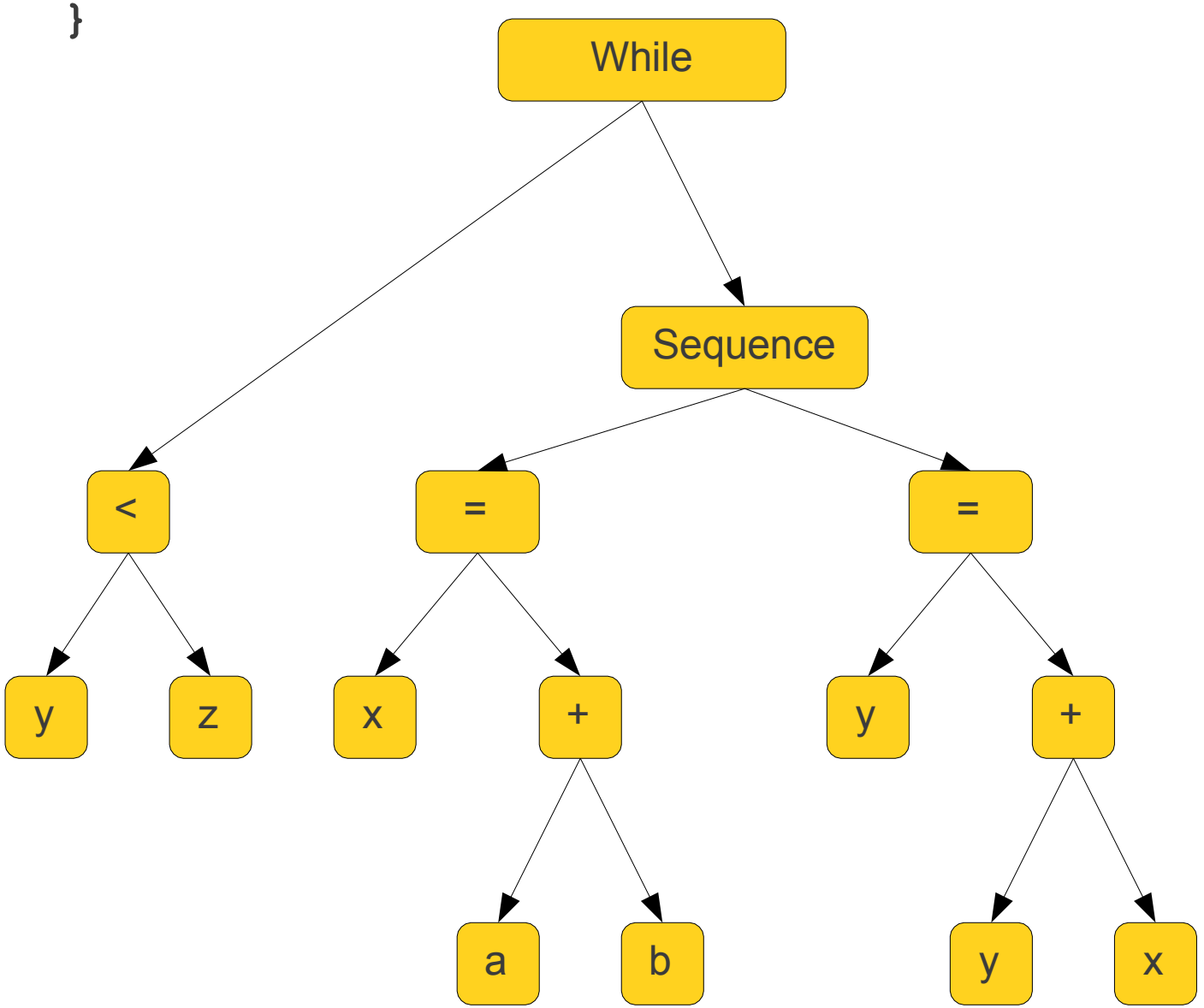

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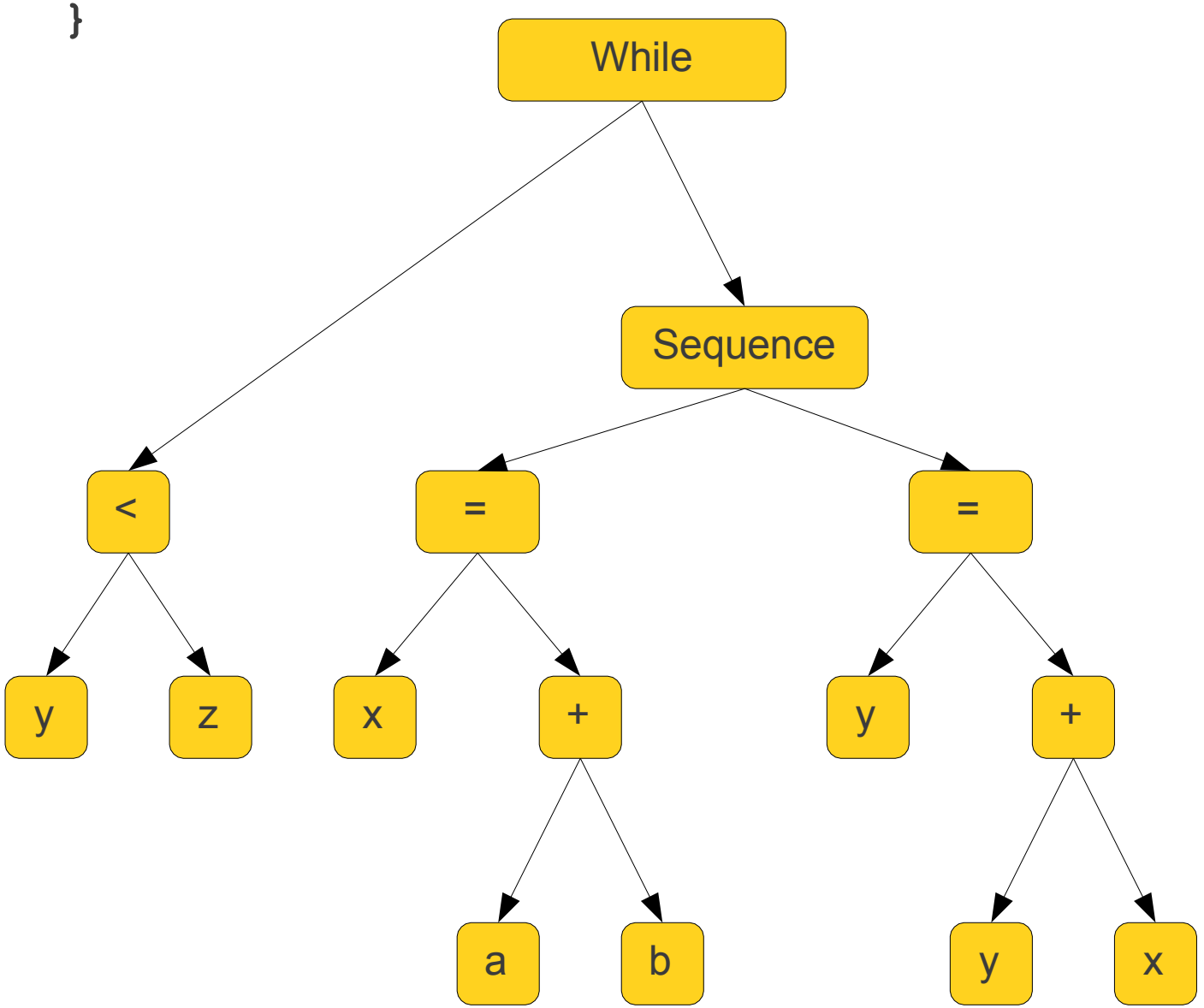

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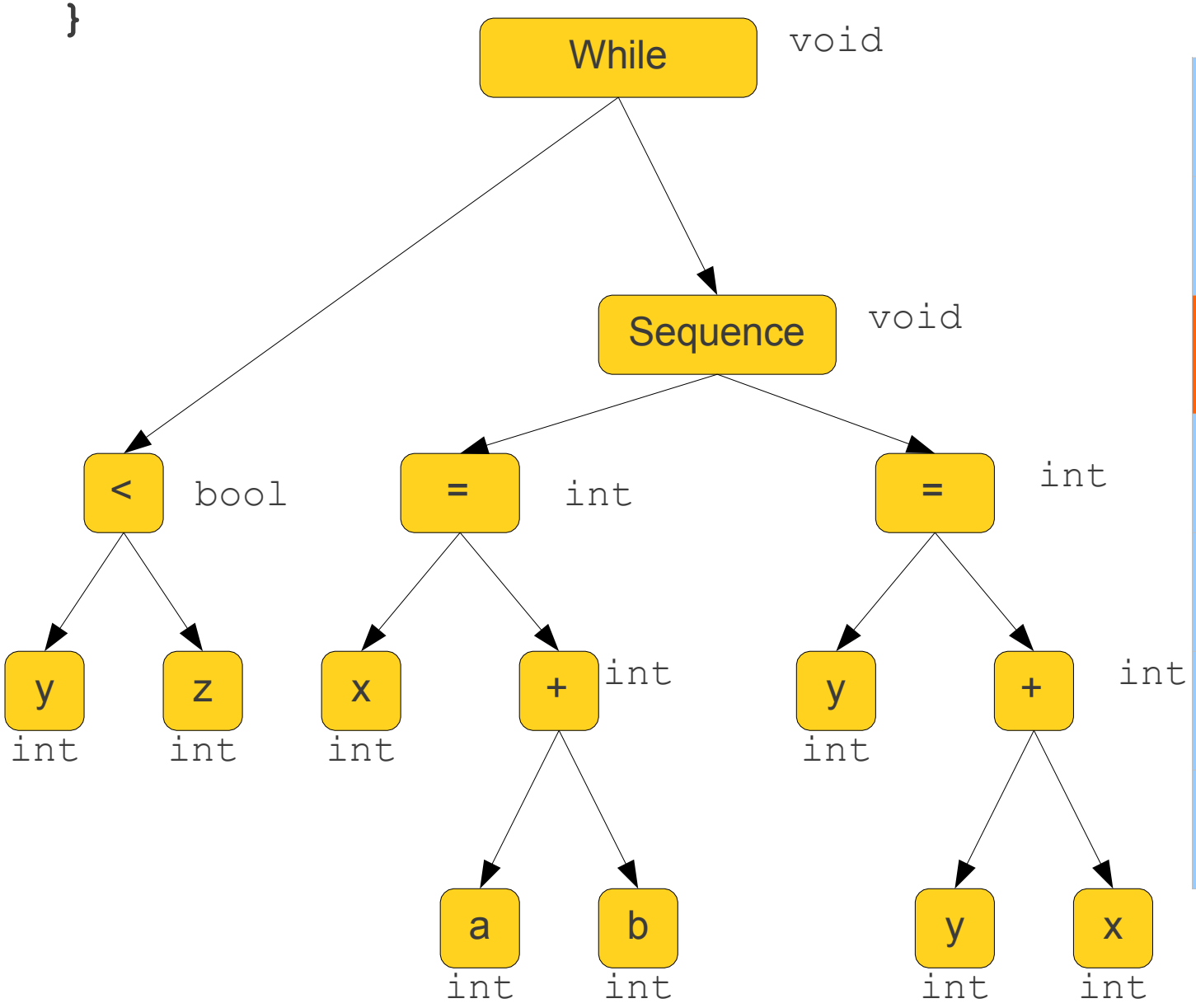

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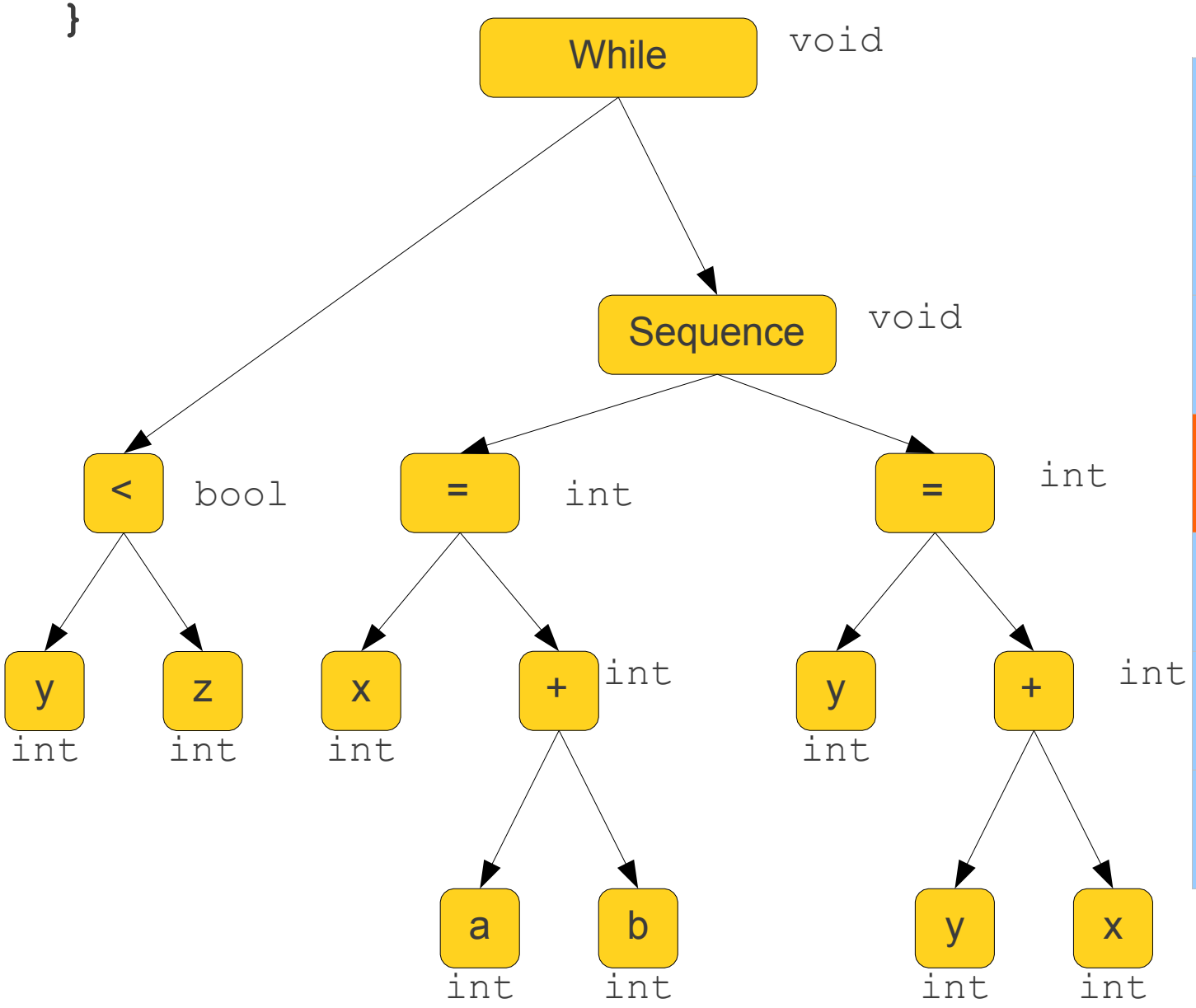

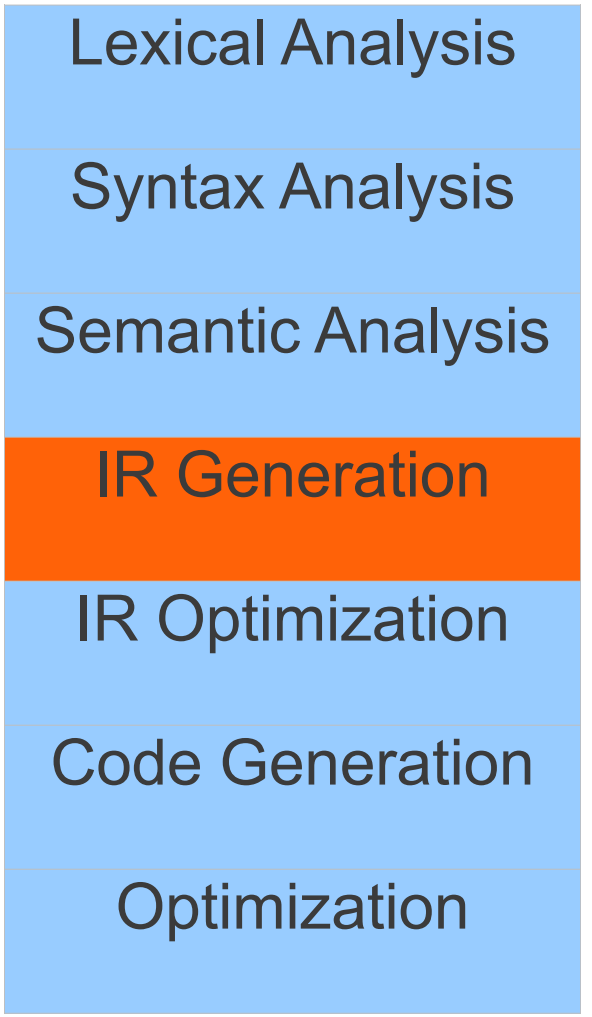

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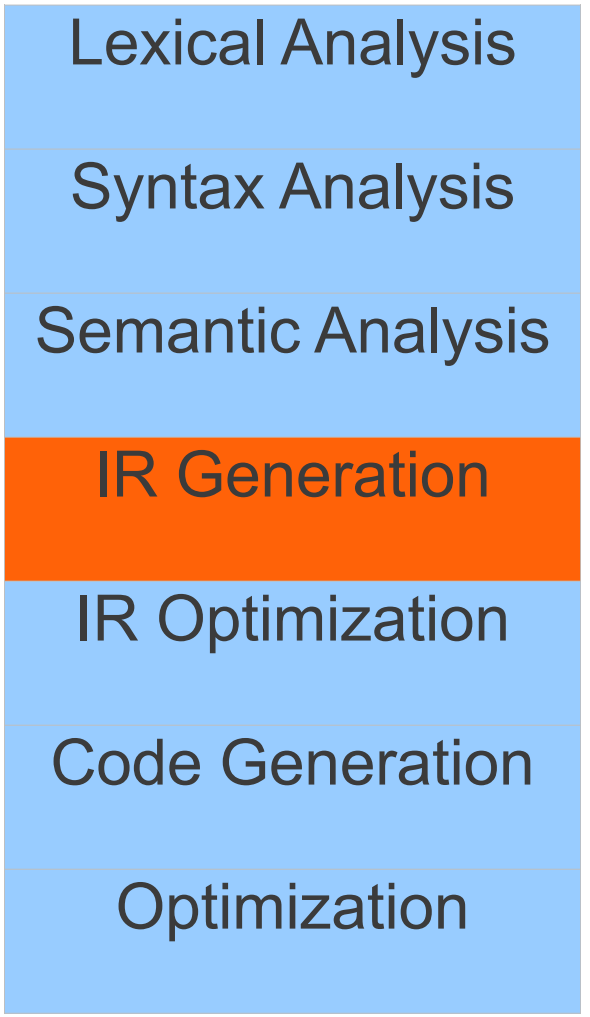
Loop: x    = a+b
      y    = x+y
      _t1 = y < z
      if _t1 goto Loop
```



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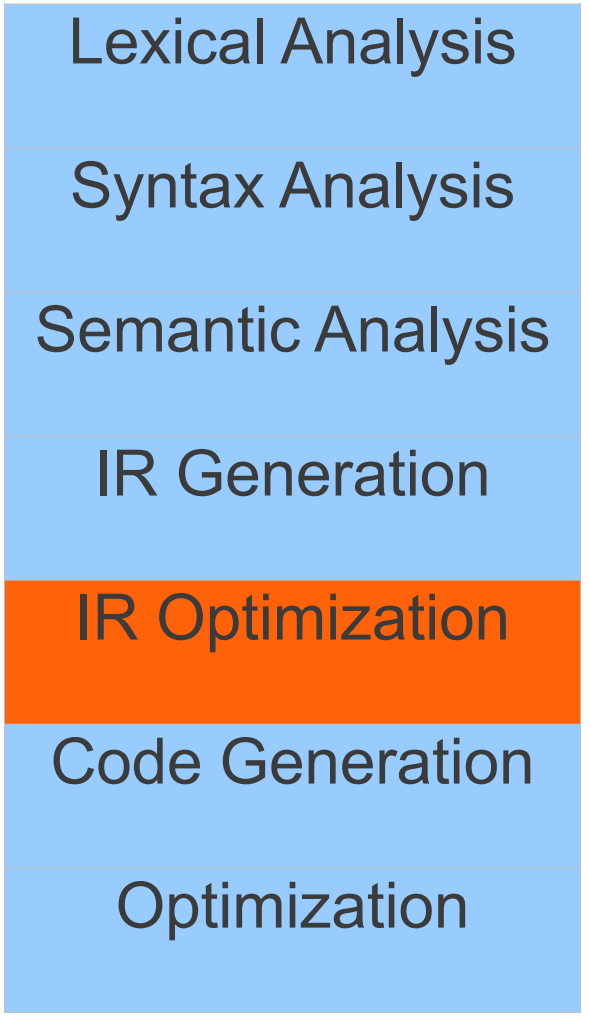

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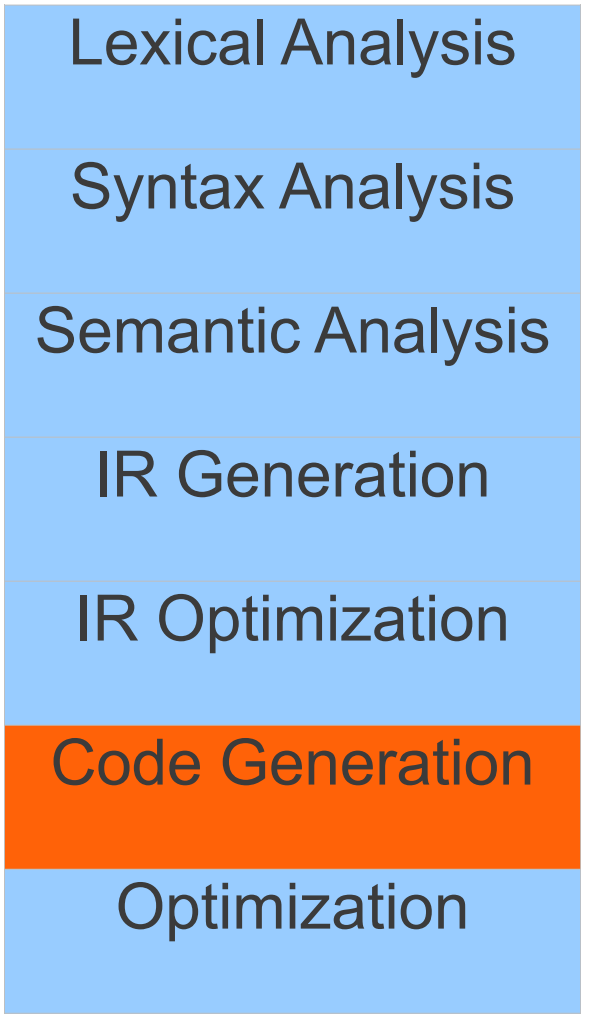

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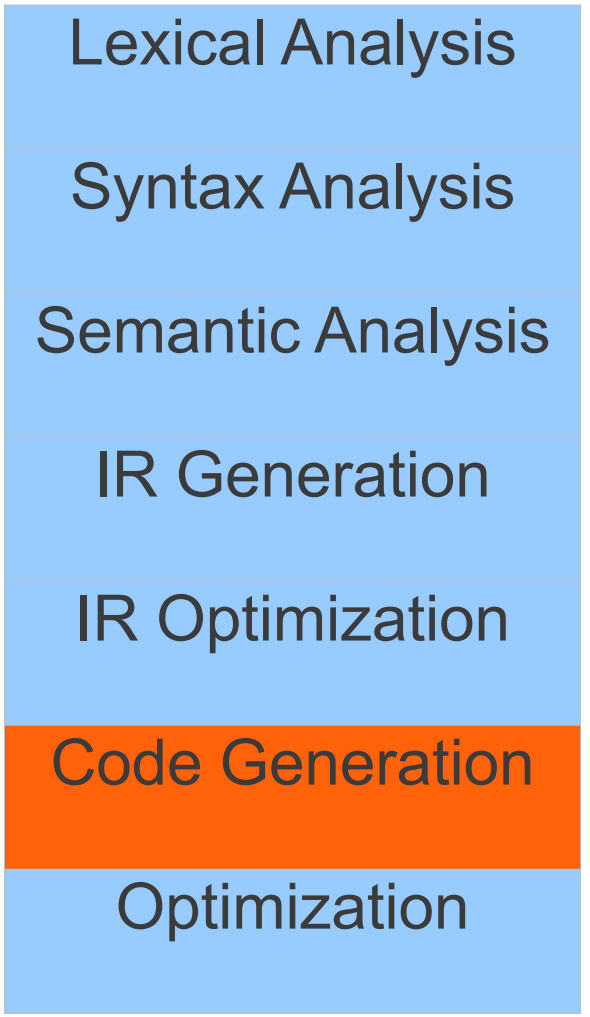
```
        add $1, $2, $3
Loop:   add $4, $1, $4
        slt $6, $4, $5
        beq $6, loop
```



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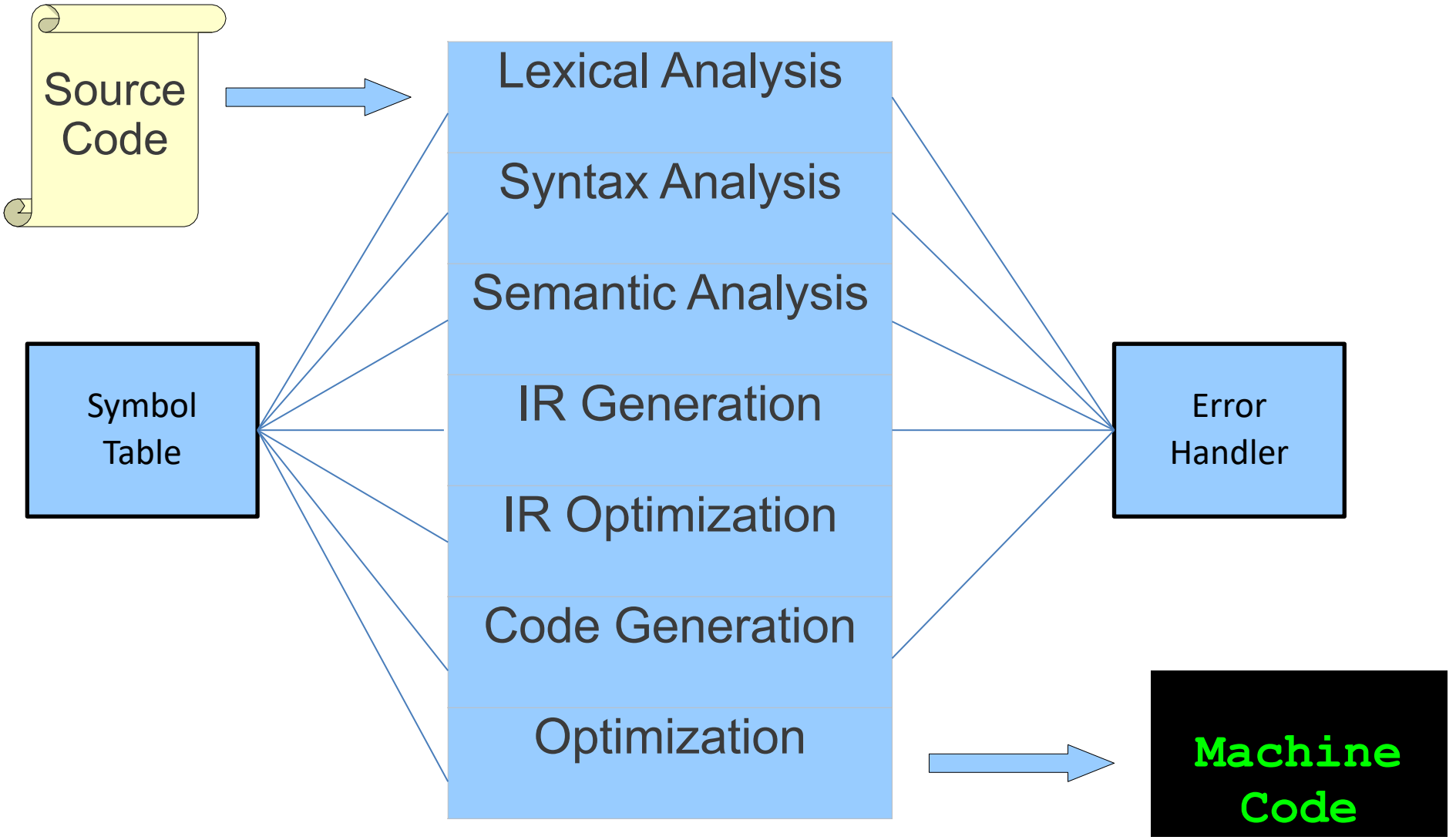
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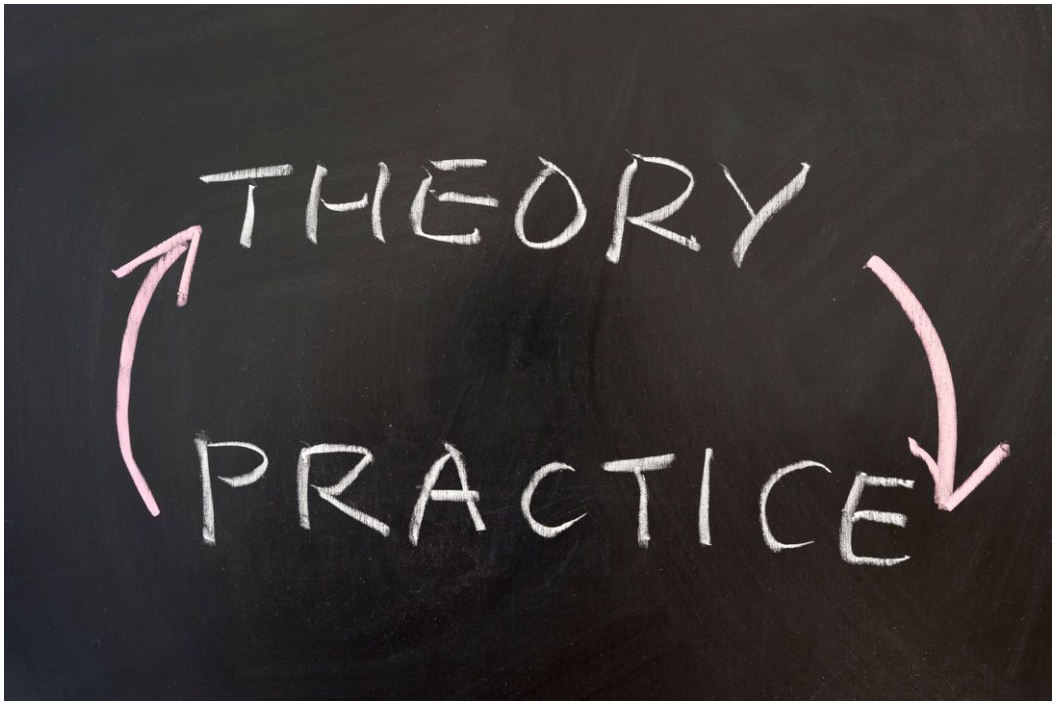
Symbol Table
Error Handler
Machine Code

Course Theme

- Studying design and implementation a very complicated software.
- We break it apart!
- We are going to meet weird-useful language features.

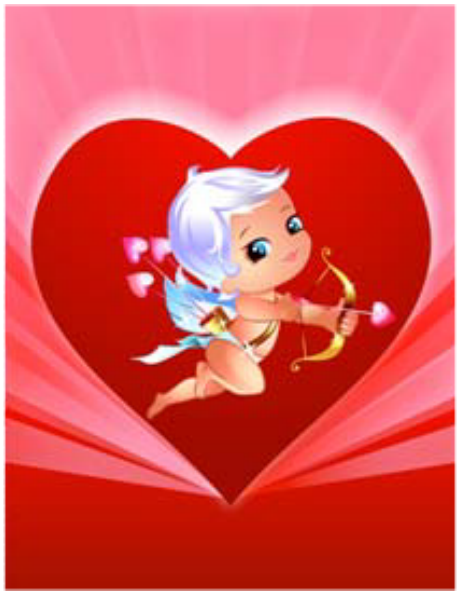
Course Theme

- We use theory as much as possible to survive.
- Excellency at programming is needed.



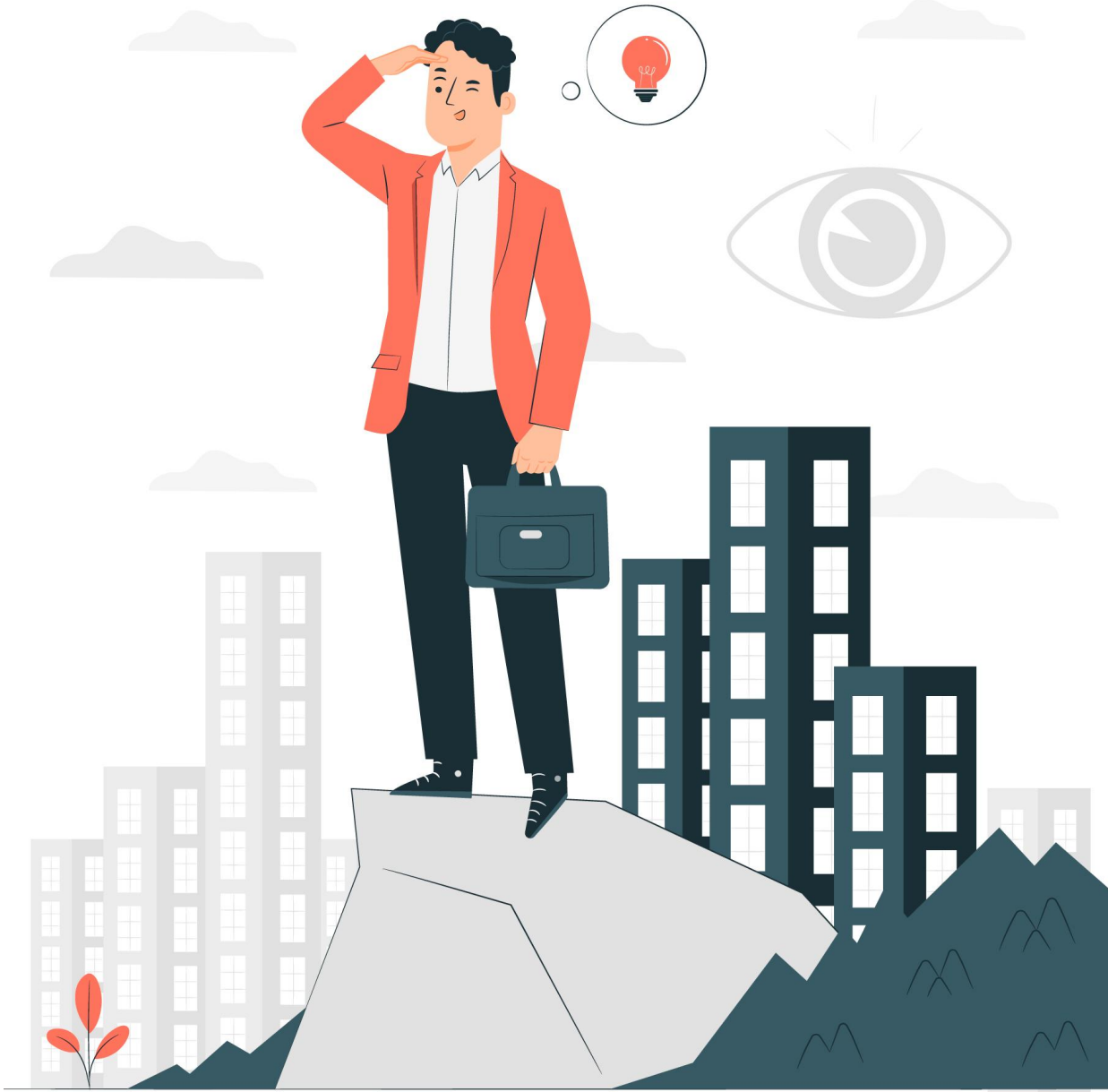
Why Take Programming Languages and Compilers?

To appreciate the marriage of theory and practice



"Theory and practice are not mutually exclusive; they are intimately connected. They live together and support each other." **[D.E. Knuth, 1989]**

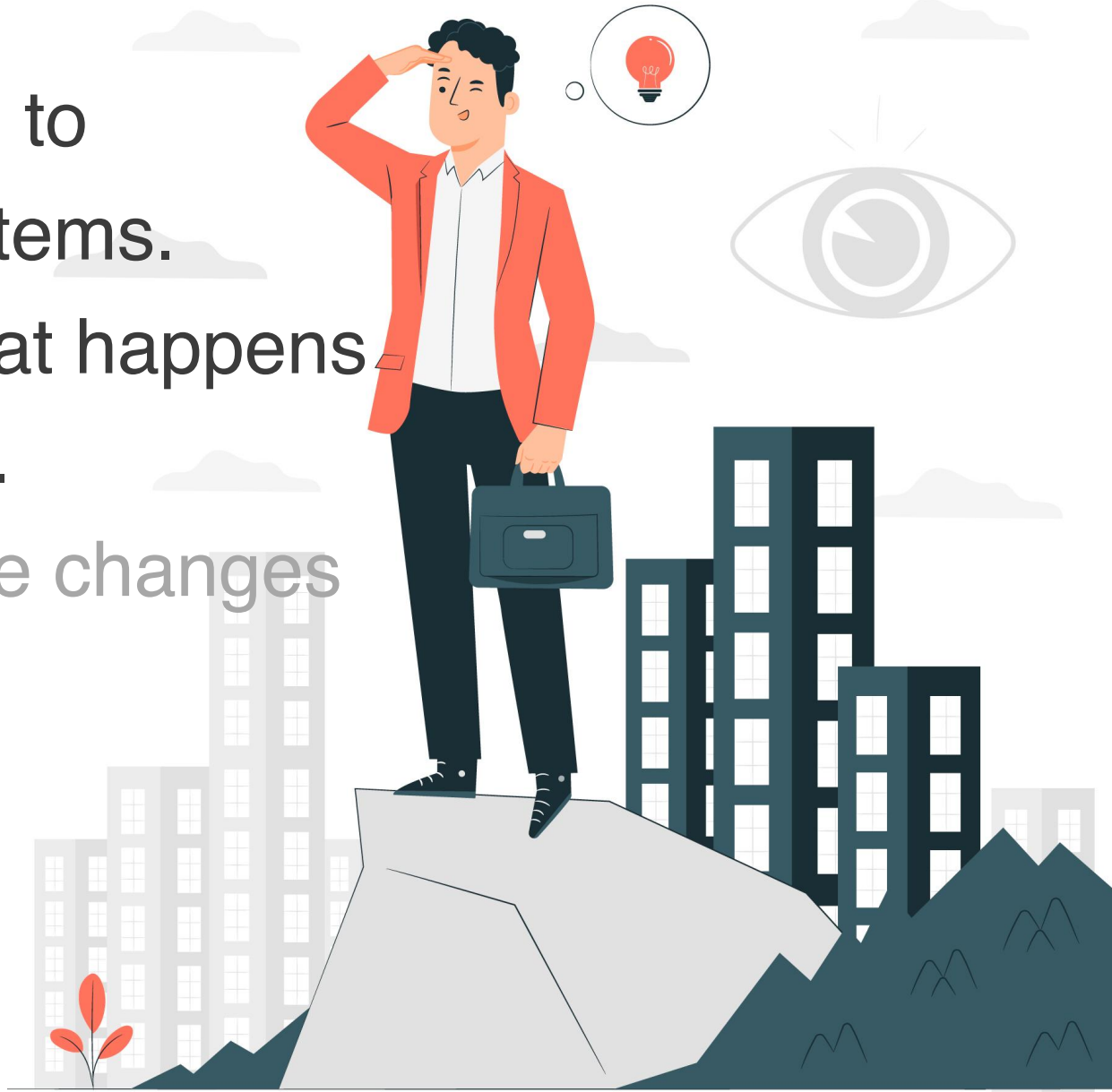
Why Study Compilers?



Why Study Compilers?

We Seek for a vision to

- build better systems.
- Understand what happens under the hood.
- Cope with future changes and era.



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- Build a **large, ambitious software system**.

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- Compiler Study Trains **Good Developers**.

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- Build a **large, ambitious software system**.
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- See theory **come to life**.

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- Learn **tradeoffs in language design**.

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This Course Adapted form Stanford CS 143 And MIT CS 6.s081

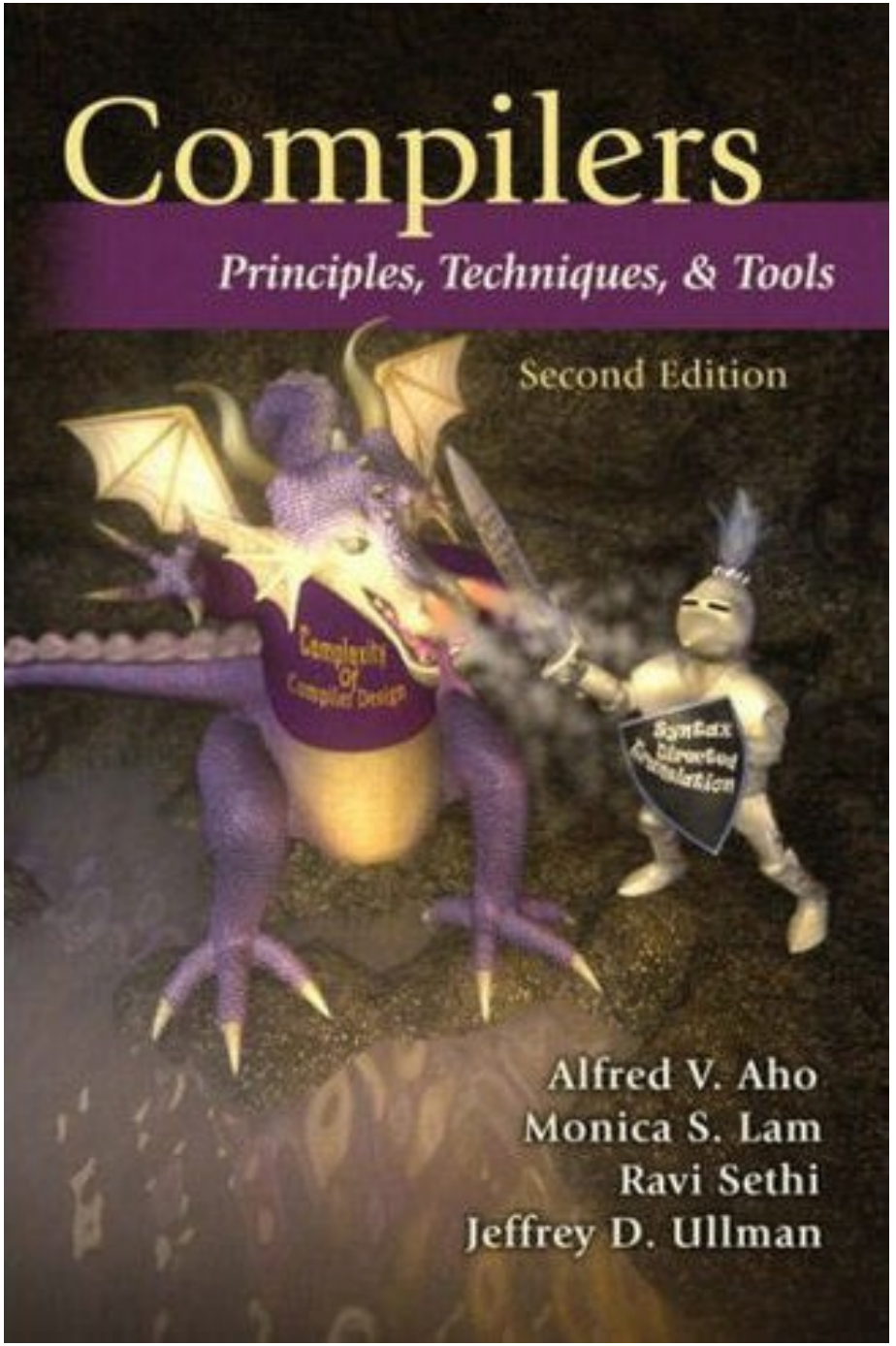
(but with changes!)

TA: Soroosh Zare

(ihaveint [] gmail)

Course Page: http://foroughmand.ir/?page_id=819

- Course info
- Important Announcements
- Calendar
- Some resources


Compilers
Principles, Techniques, & Tools
Second Edition
Alfred V. Aho
Monica S. Lam
Ravi Sethi
Jeffrey D. Ullman

- We use Quera and CW.

- We use Quera and CW.
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2+2=4
LIVE

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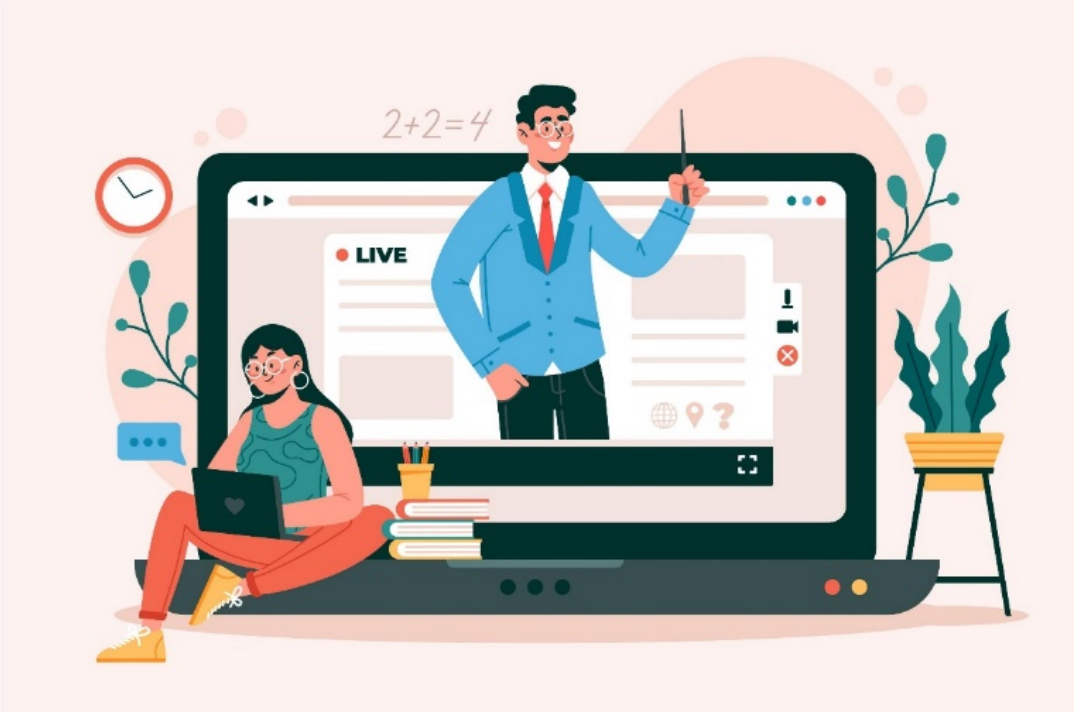

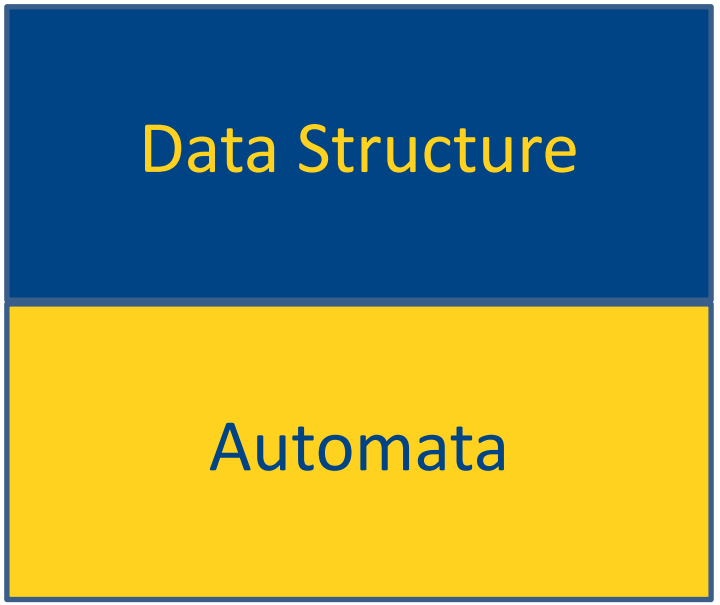

Maturity in programming and patience is also required.

بارم‌بندی

- تمرین: ۴ نمره
- آزمونک: ۲ نمره
- پروژه: ۶ نمره
- میان‌ترم: ۲ نمره
- پایان‌ترم: ۶ نمره

Homework

- About 7 assignments.
- About 2 weeks each
- About 3 problems.

- Do not postpone until the deadline!

- You have 10 days for late submission allowance.

LaTeX

Exams (mid-term, final, and Quiz)

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- Reasonable exams, if you study you can get a good mark.

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Exams

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- Open book and lectures in online exam.

Exams

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- On regular, you can bring on paper.

Exams (mid-term, final, and Quiz)

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- Mid-term: ٠٠/١٢/٢٣

Exams (mid-term, final, and Quiz)

- Mid-term: ٠٠/١٢/٢٣

Mini Quiz

- 2 Quizes
- With announcement.
- Takes 30 min.
- Not in group. Open slides.
- From previous or current lectures.
- Rules of mid-term and final applies.

Project

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- It is a complete compiler in 3-4 phases.
  - Lexical Analyzer (Scanner)
  - Parser
  - Code Generation

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LINUX

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- This course has a big project. It is not easy. And, It might be time-consuming. Also, It requires patience and carefulness.

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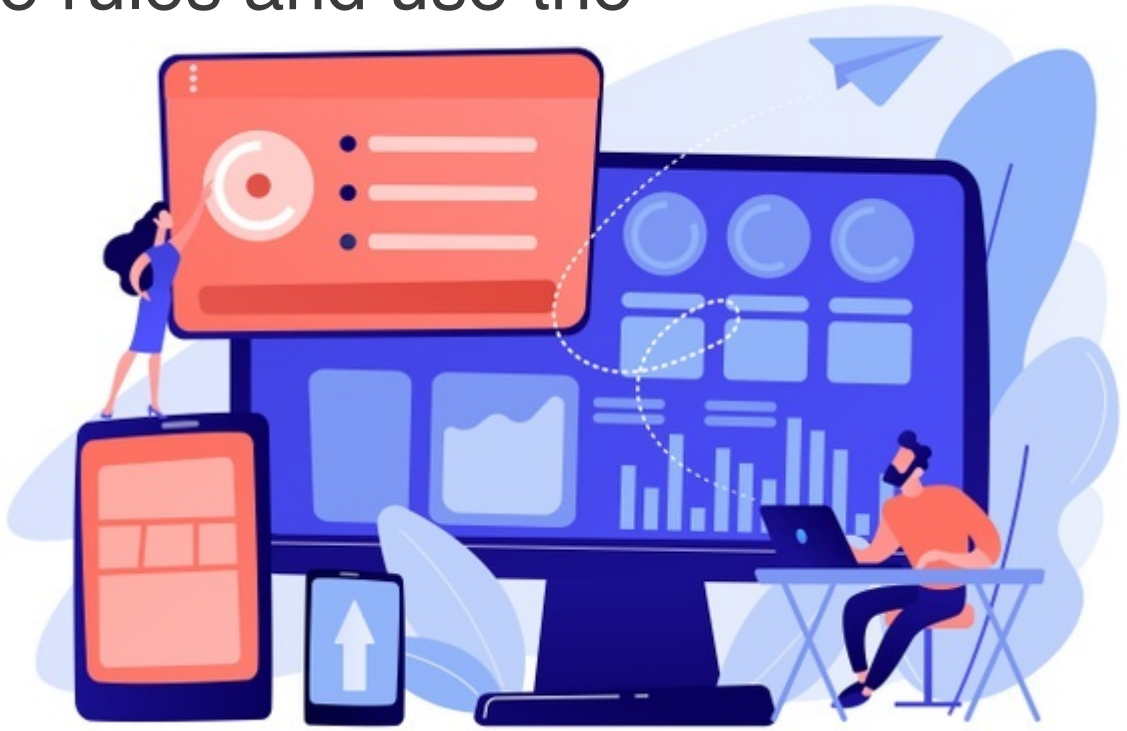
- Project must follow the rules and use the framework.



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- We check just your outputs while grading. Especially in phase 3, your generated program **MUST** work correctly.

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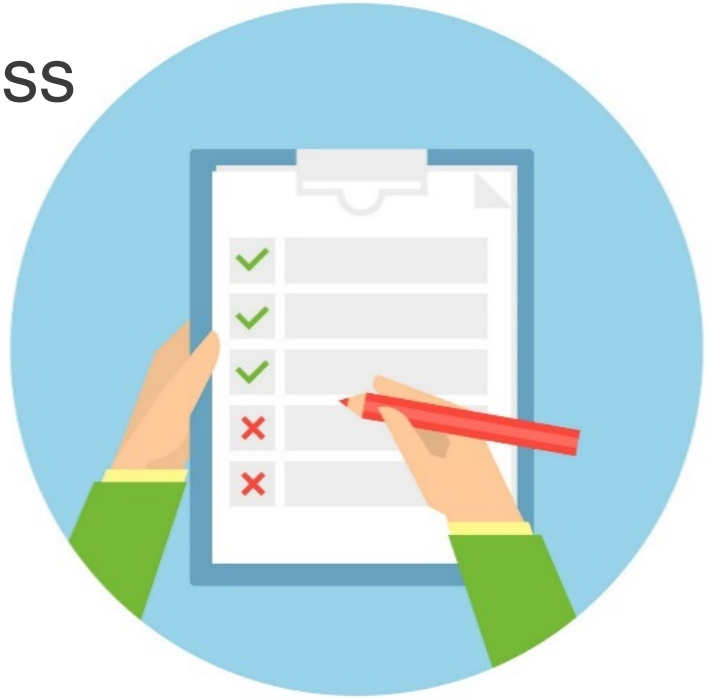
- We have many tests either you pass or fail each one.



Submission Guide line

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- Don’t postpone everything to the last second (Parkinson’s Law).

Submission Guide line

- Just submit once unless you contact with the corresponding assistant.
- Don’t postpone everything to the last second (Parkinson’s Law).
- Just upload it to **Quera** or **CW**. E-mails lost usually.

Project team

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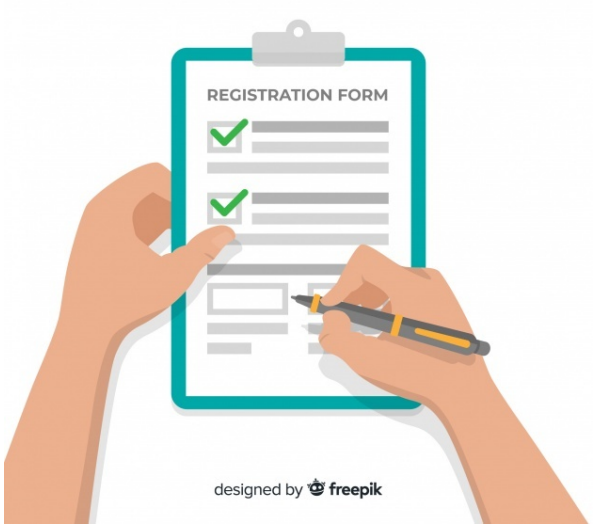
- Team of two or one person.

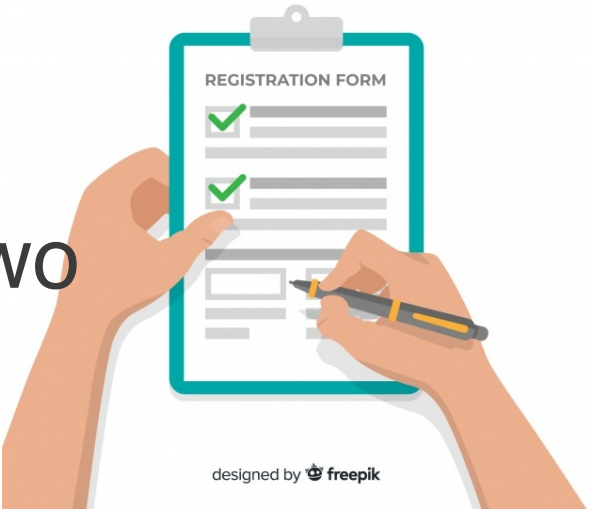
Group Rules


REGISTRATION FORM
designed by freepik


HELPFUL
TIPS!
designed by freepik.com

Group Rules

- Projects are for groups of one or two students.



Group Rules

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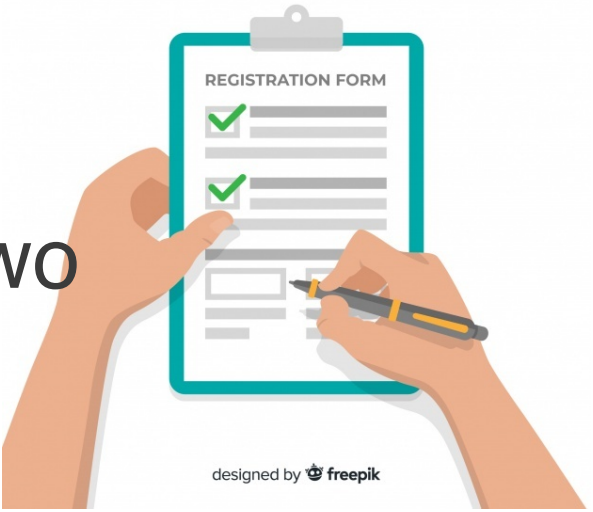
- Pick an innovative name.



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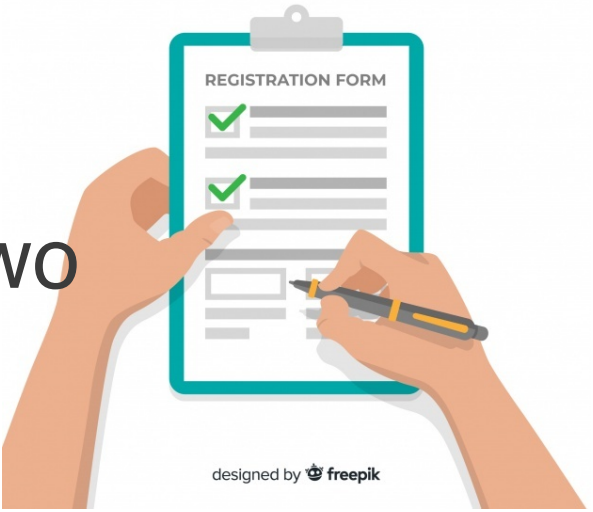

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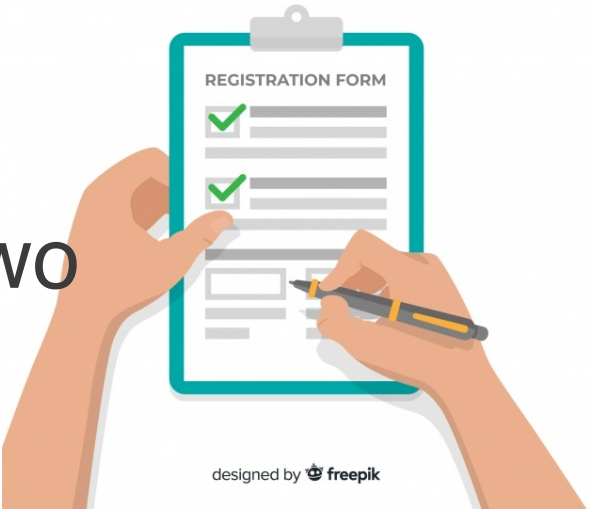

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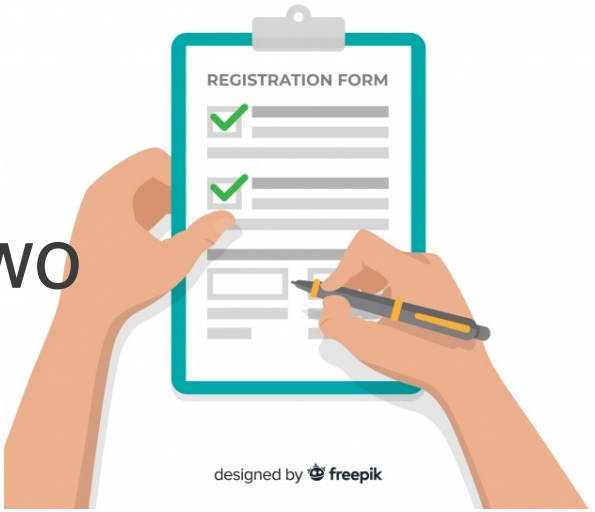

- Projects are for groups of one or two students.
- Pick an innovative name.
- Register Here.

- A piece of advice: create a group with friends with whom you can work easily.

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- There is a delivery and we check it there.

تقلب

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- You can use your book and notes during online exams. But you must obtain them before the exam.

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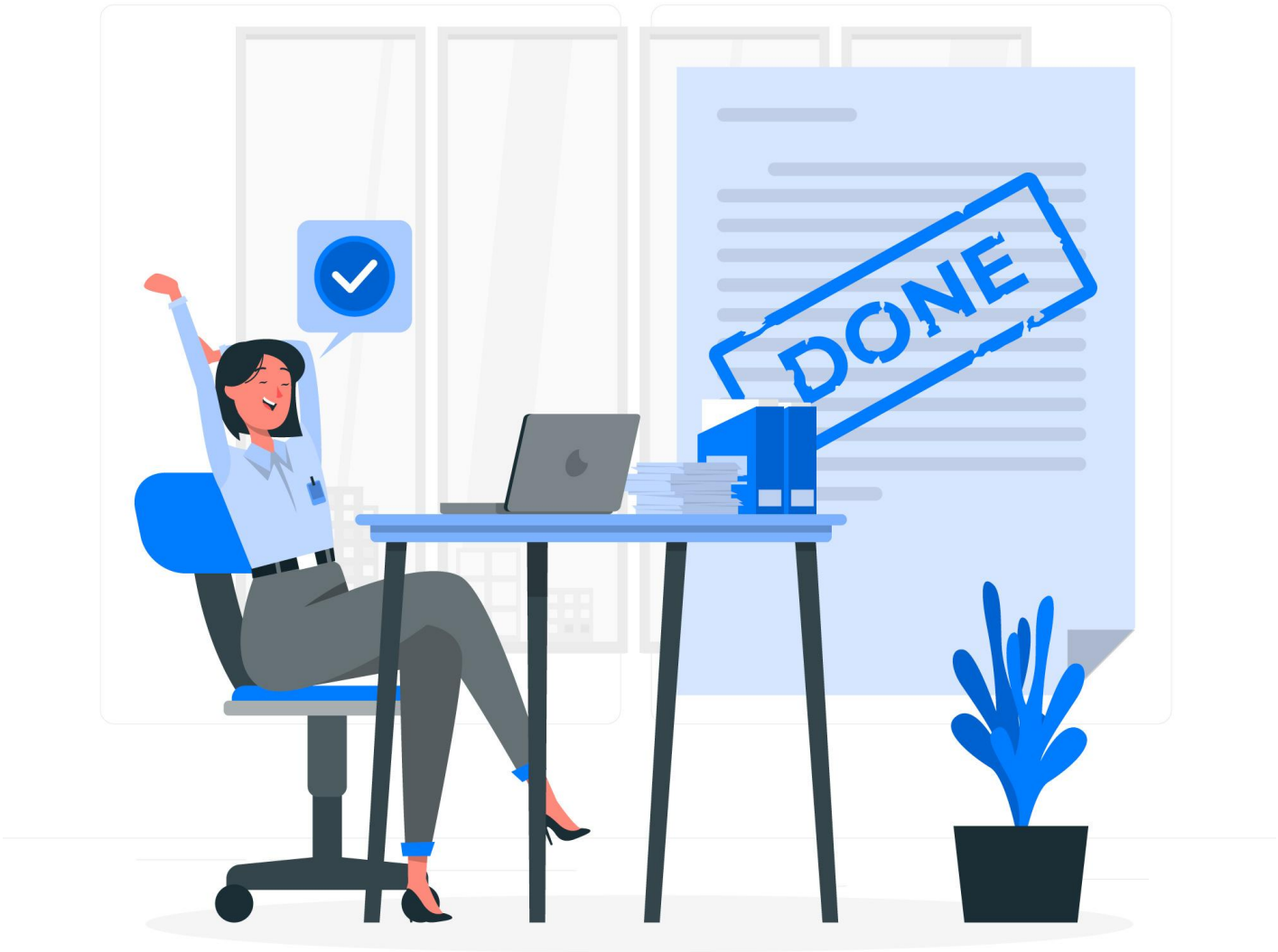
- If we see any violation our reaction will be hard.

فیلم دکتر خسروی

What happens if…

- In projects the penalty is a -100 grade.
- In homework, plagiarism have a -100 grade.
- In the exams/quiz (One of these can occurs):
  - Send it to education affairs (you may receive 0.25 as the final grade).
  - Fail the course.
  - 0/-100 for the whole exam.
  - -100 for the question
    - in exceptional cases
- And no extra grade, if we decide.

PHD Comics: Extension


DONE