信息科学与技术学院
School of Information Science and Technology

CS 110
Computer Architecture
Everything is a Number

Instructors:

Siting Liu & Chundong Wang

Course website: https://toast-lab.sist.shanghaitech.edu.cn/courses/CS110@ShanghaiTech/Spring-2023/index.html

School of Information Science and Technology (SIST)

ShanghaiTech University

2023/2/6

Course Info

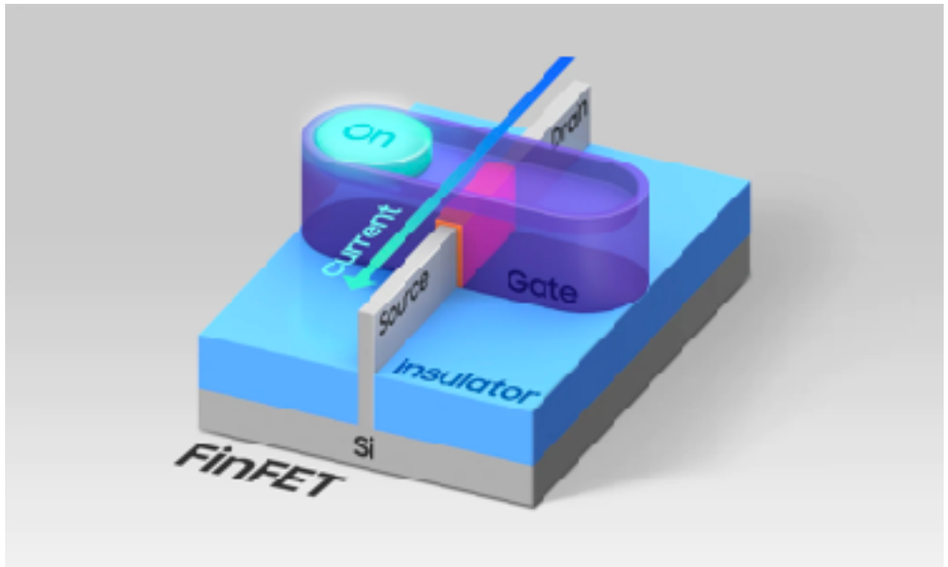
- **HW1 is available, Due Feb. 16th!**
- **Team (Lab & project) partners are required to be within the same lab session! Decide before Feb. 11th!**
- **Acknowledgement**: **UC Berkeley's CS61C: https://cs61c.org/**; 国科大一生一芯: https://ysyx.oscc.cc/
- https://piazza.com/shanghaitech.edu.cn/spring2023/cs110 (access code: **uutib6ruvql**)
- Textbooks: Average 15 pages of reading/week
  - Patterson & Hennessey, Computer Organization and Design **RISC-V edition**!
  - Kernighan & Ritchie, The C Programming Language, 2nd Edition
  - RTFM: C & RISC-V
- Materials this year are similar to previous years, but there might be differences!
- https://robotics.shanghaitech.edu.cn/courses/ca/22s/

Outline

- Binary system
- Everything is a number
- Signed and Unsigned integers
- Tow's-complement representation

Binary System

- 0 and 1
- Decided by the characteristic of semiconductor devices (bi-stable states)
- Resilient to noise (threshold)
  - Two branches of math theory
  - Can do logic and arithmetic
- Analogy to decimal (to represent values)
- Positionally weighted coding
- Binary-decimal conversion
- Extend to Hexadecimal (Base 16)/Octal (Base 8)



Arithmetic

$$\begin{array}{r} 0011 \\ +\ 0010 \\ \hline \end{array} \qquad \begin{array}{r} 1100 \\ -\ 1010 \\ \hline \end{array}$$

$$\begin{array}{r} 1101 \\ \times\ 1110 \\ \hline \end{array}$$

$$110 \overline{)\,10101111}$$

Everything is a Number

- Inside computers, everything is a number
- But numbers usually stored with a fixed size
  - 4-bit nibbles (rarely used), 8-bit bytes, 16-bit half words, 32-bit words, 64-bit double words, ...

Everything is a Number

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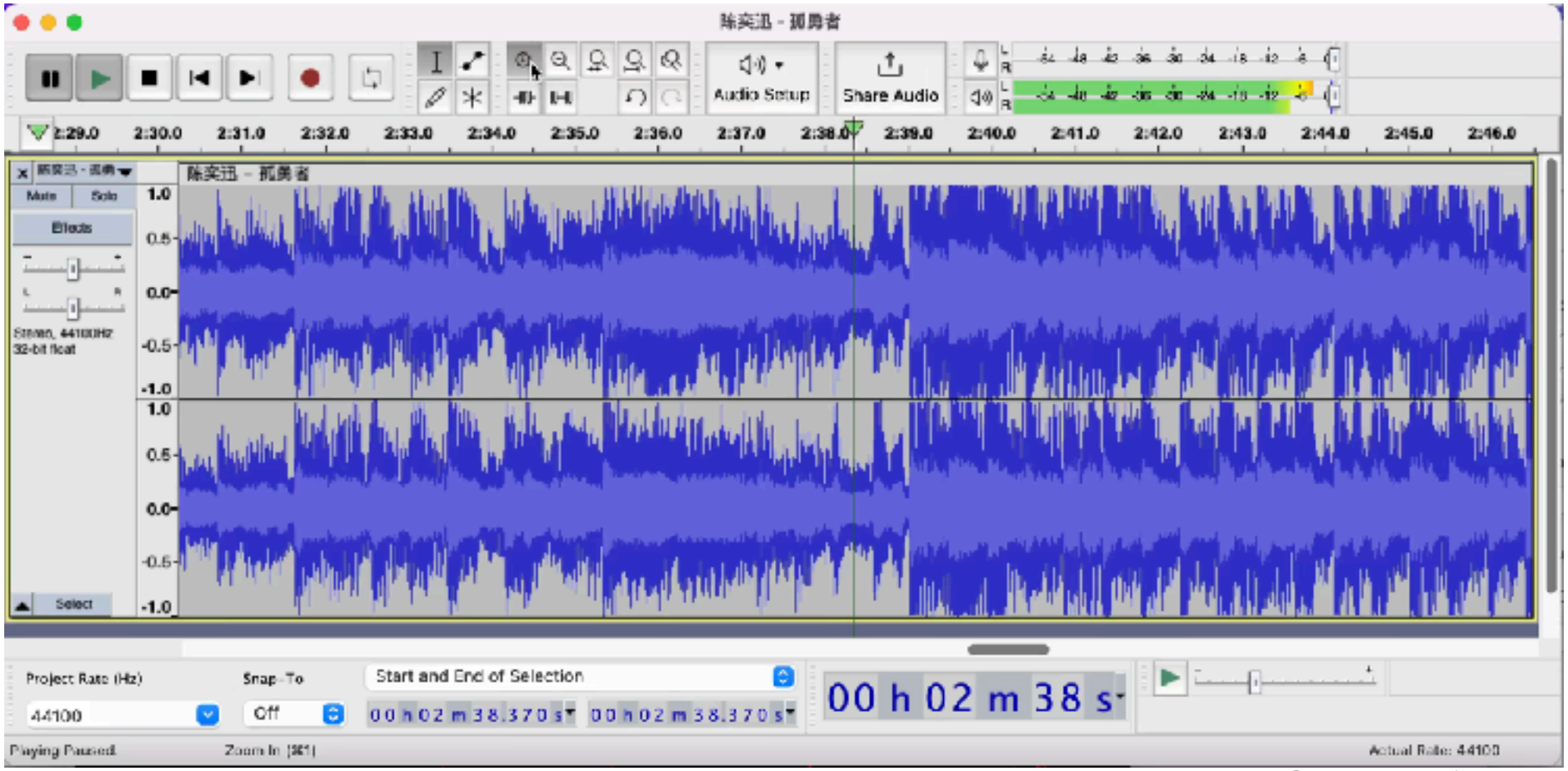
- But numbers usually stored with a fixed size
  - 4-bit nibbles (rarely used), 8-bit bytes, 16-bit half words, 32-bit words, 64-bit double words, ...
- Integer and floating-point operations can lead to results too big/small to store within their representations: overflow
- To avoid overflow, use more bits or extend the range by interpreting a number differently

Everything is a Number

Soundtrack sampled at 44.1 kHz

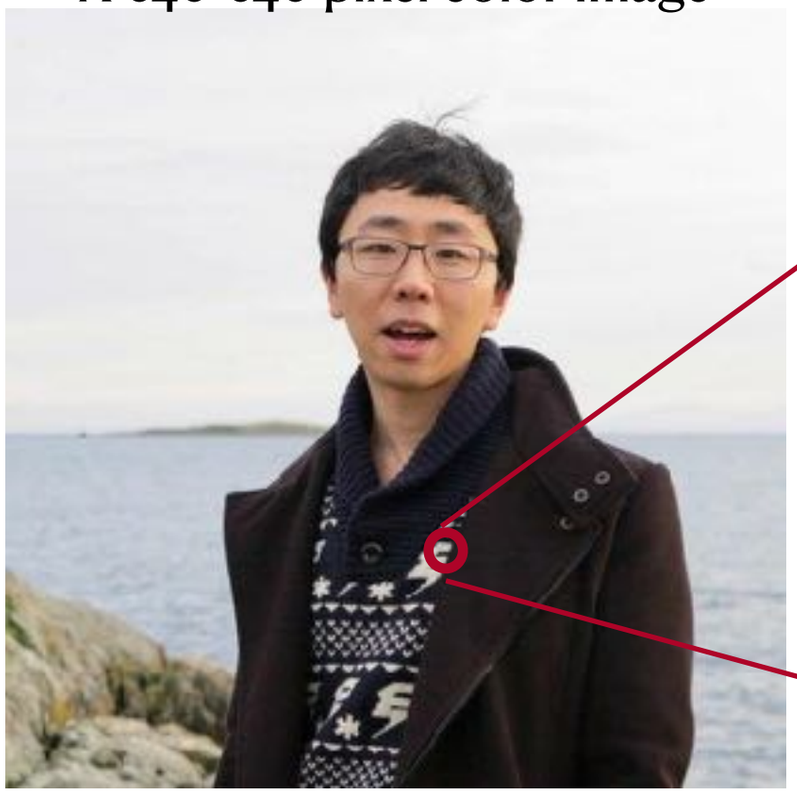


from Audacity

Everything is a Number

- Inside computers, everything is a number
- But numbers usually stored with a fixed size
  - 4-bit nibbles (rarely used), 8-bit bytes, 16-bit half words, 32-bit words, 64-bit double words, ...

A 640*640 pixel color image



Around 60 KB on disk

https://www.graphicsmill.com/blog/2014/11/06/Compression-ratio-for-different-JPEG-quality-values

HEX: #c6c3ba
RGB(198, 195, 186)

A 20*20 part of the color image

HEX: #292023
RGB(41, 32, 35)

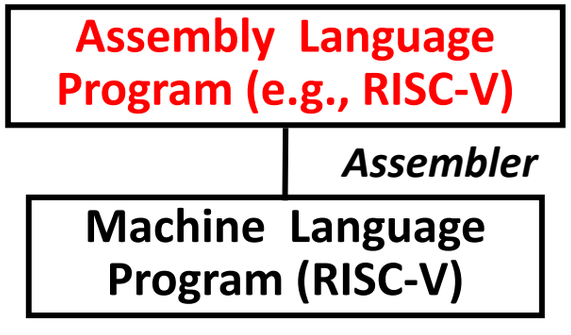
HEX: #d5d2c9
RGB(213, 210, 201)

Everything is a Number

- Inside computers, everything is a number (but not necessary the value)
- But numbers usually stored with a fixed size
  - 4-bit nibbles (rarely used), 8-bit bytes, 16-bit half words, 32-bit words, 64-bit double words, ...
- Identity, bank account, profile, ...
  - ID number, DoB (date of birth), criminal record, mobile, etc.
  - Bank account numbers, balance, loan, transaction records, etc.
  - Game account, coins, equipments, ...

Everything is a Number

- Inside computers, everything is a number (but not necessary the value)
- But numbers usually stored with a fixed size
  - 4-bit nibbles (rarely used), 8-bit bytes, 16-bit half words, 32-bit words, 64-bit double words, …
- Instructions: e.g., move direction: forward, backward, left, right; use $(00)_2$, $(01)_2$, $(10)_2$ and $(11)_2$



Stored program

```
lw   t0, 0(s2)
lw   t1, 4(s2)
sw   t1, 0(s2)
sw   t0, 4(s2)
```

Anything can be represented as a *number*, i.e., data or instructions

ISA, defined by human, decides the meaning

```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```

- It is how you interpret the numbers decides the meaning

Signed and Unsigned Integers

- Commonly used in computers to represent integers
- C, C++ have signed integers, e.g., 7, -255:
  - int x, y, z;
- C, C++ also have unsigned integers, e.g. for addresses
- Unsigned integers use their values to represent numbers directly
- Unsigned integers in 32 bit word represent
  0 to 2^{32}-1 (4,294,967,295) (4 Gibi)

Unsigned Integers

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 0_{ten}$

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 1_{ten}$

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = 2_{ten}$

… …

$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{two} = 2{,}147{,}483{,}645_{ten}$

$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = 2{,}147{,}483{,}646_{ten}$

$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 2{,}147{,}483{,}647_{ten}$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 2{,}147{,}483{,}648_{ten}$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 2{,}147{,}483{,}649_{ten}$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = 2{,}147{,}483{,}650_{ten}$

… …

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{two} = 4{,}294{,}967{,}293_{ten}$

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = 4{,}294{,}967{,}294_{ten}$

$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 4{,}294{,}967{,}295_{ten}$

$$(a_n a_{n-1} \ldots a_1 a_0)_2 = a_n \cdot 2^n + a_{n-1} \cdot 2^{n-1} + \cdots + a_1 \cdot 2^1 + a_0 \cdot 2^0$$

Signed Integers

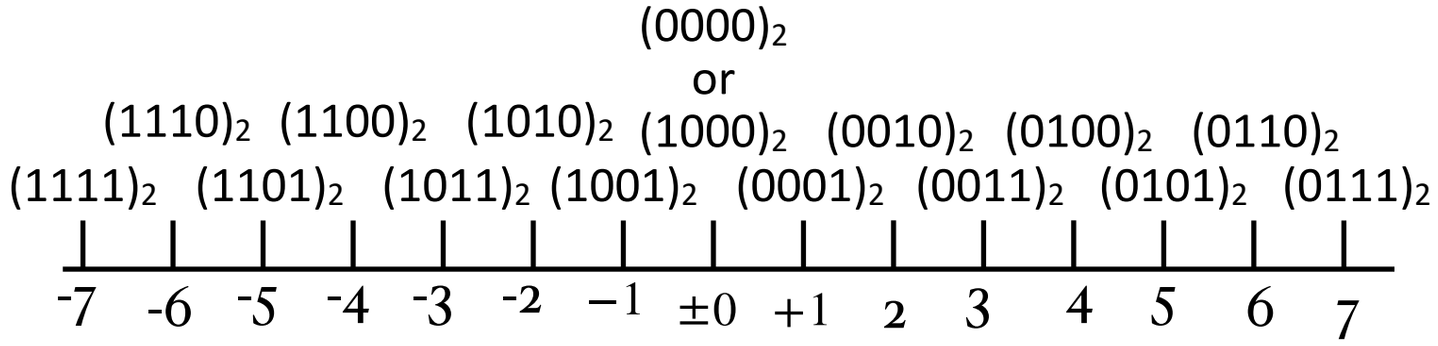
- A straight-forward method: add a sign bit (sign-magnitude)
- Most-significant bit (MSB, leftmost) is the sign bit, 0 means positive, 1 means negative; the other bits remain unchanged

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0011_{two} = 3_{ten}$

$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0011_{two} = -3_{ten}$

Sign bit

- Range:
  - Positive: 0 ~ $2^{(n-1)}-1$
  - Negative: -0 ~ $-(2^{(n-1)}-1)$
  - Arithmetically unfriendly



Signed Integers

One's- & Two's-Complement Representation

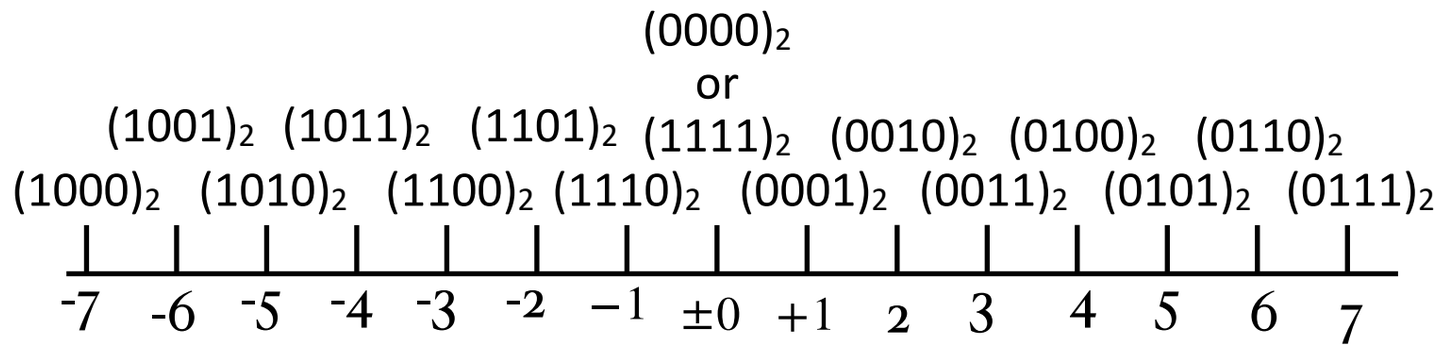
- One's-complement representation
  - Positive numbers, stay unchanged; Negative numbers, toggle all bits

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0011_{two} = 3_{ten}$

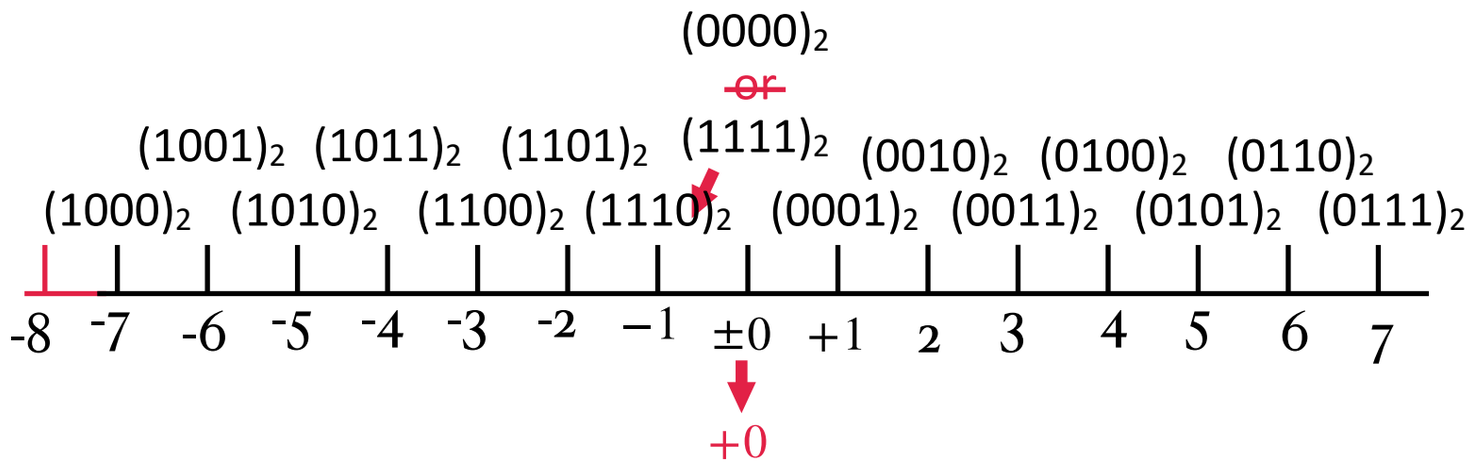
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1100_{two} = -3_{ten}$

Sign bit

- Range:
  - Positive: $0 \sim 2^{(n-1)}-1$
  - Negative: $-0 \sim -(2^{(n-1)}-1)$
  - Arithmetically unfriendly



Two's-Complement Representation (Signed Integer)



- Two's-complement representation:

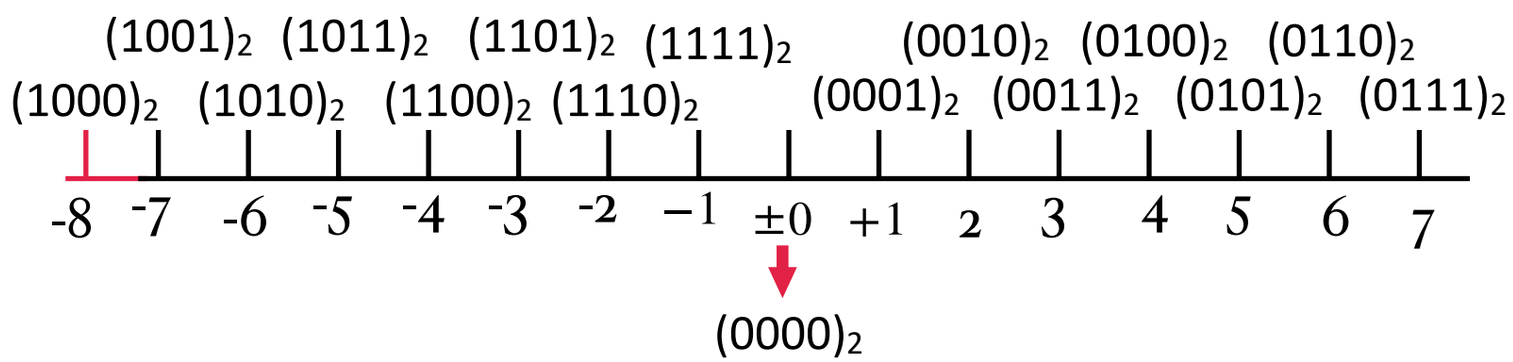
- Positive numbers, stay unchanged; Negative numbers, apply two's complement (for an n-bit number A, complement to 2^n is 2^n-A, or toggling all bits and adding 1)

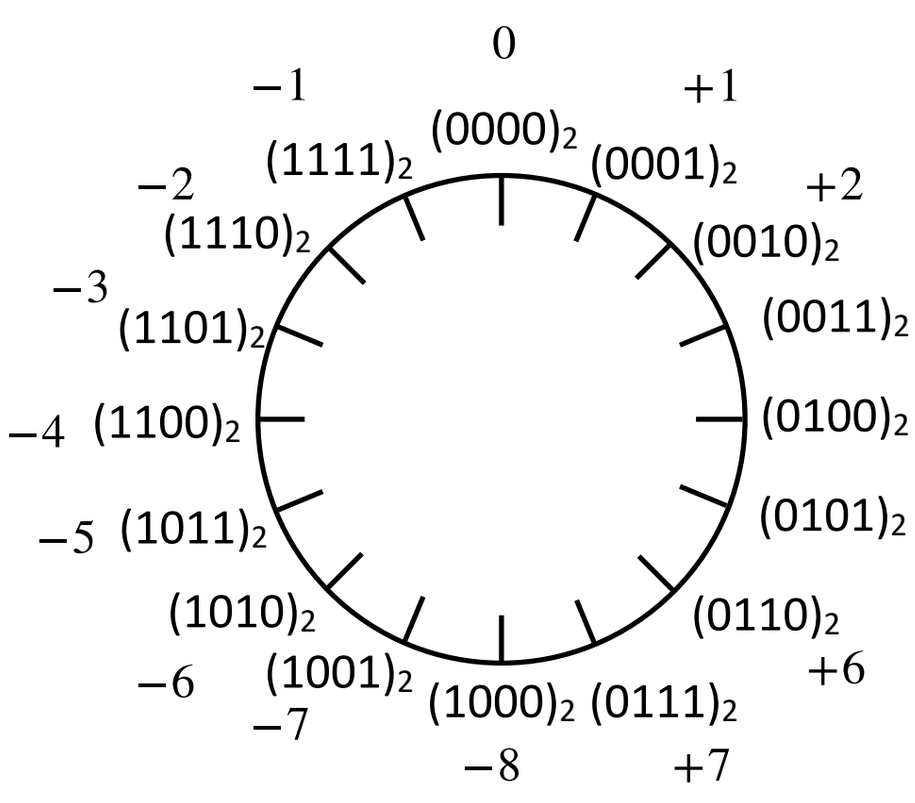
0000 0000 0000 0000 0000 0000 0000 $0011_{two} = 3_{ten}$

1111 1111 1111 1111 1111 1111 1111 $1101_{two} = -3_{ten}$

Sign bit

Two's-Complement Representation (Signed Integer)





- 2'complement number $(a_n a_{n-1} \ldots a_1 a_0)_2$ represents

$$(a_n a_{n-1} \ldots a_1 a_0)_2 = -a_n \cdot 2^n + a_{n-1} \cdot 2^{n-1} + \cdots + a_1 \cdot 2^1 + a_0 \cdot 2^0$$

- Sign extension
- Arithmetics

Two's-Complement Arithmetic (Addition & Subtraction)

3 0011	3 0011	-3 1101
+2 0010	+ (-2) 1110	+ (-2) 1110
7 0111		-8 1000
+1 0001		+ (-1) 1111

- Overflow check!

Comparison

Sign-magnitude	One's-complement	Two's-complement
5 0101	5 0101	5 0101
+ (-3) 1011	+ (-3) 1100	+ (-3) 1101
0000	0001	0010
✗	✗	✓

Two's-Complement Representation (Signed Integer)

- Two's complement treats 0 as positive, so 32-bit word represents 2^{32} integers from
  -2^{31} (–2,147,483,648) to $2^{31}-1$ (2,147,483,647)
  - Note: one negative number with no positive version
  - **Every computer uses two's complement today**
- Most-significant bit (MSB) (leftmost) is the sign bit, since 0 means positive (including 0), 1 means negative
  - Bit 31 is most significant (MSB), bit 0 is least significant (LSB)

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CS 110
Computer Architecture
Intro to C I

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Course website: https://toast-lab.sist.shanghaitech.edu.cn/courses/CS110@ShanghaiTech/Spring-2023/index.html

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Introduction to C
“The Universal Assembly Language”

Intro to C

- C *is not a "very high-level" language, nor a "big" one, and is not specialized to any particular area of application. But its absence of restrictions and its generality make it more convenient and effective for many tasks than supposedly more powerful languages.*
- Enabled first operating system not written in assembly language: UNIX - A portable OS!

Intro to C

- *Why C?: we can write programs that allow us to exploit underlying features of the architecture – memory management, special instructions, parallelism*
- C and derivatives (C++/Obj-C/C#) still one of the most popular application programming languages after >40 years!

Disclaimer

- You will not learn how to fully code in C in these lectures! You'll still need your C reference for this course
  - K&R C is a recommendation
    - Check online for more sources
      - ANSI/ISO C standard manual (RTFM) (https://web.archive.org/web/20200909074736if_/https://www.pdf-archive.com/2014/10/02/ansi-iso-9899-1990-1/ansi-iso-9899-1990-1.pdf; http://web.archive.org/web/20030222051144/http://home.earthlink.net/~bobbitts/c89.txt)
- Key C concepts: Pointers, Arrays, Implications for Memory management
- We will use ANSI C89 – original "old school" C
  - Because it is closest to Assembly

How C program works?

High Level Language Program (e.g., C)

Compiler

Assembly Language Program (e.g., RISC-V)

Assembler

Machine Language Program (RISC-V)

Machine Interpretation

Hardware Architecture Description (e.g., block diagrams)

Architecture Implementation

Logic Circuit Description (Circuit Schematic Diagrams)

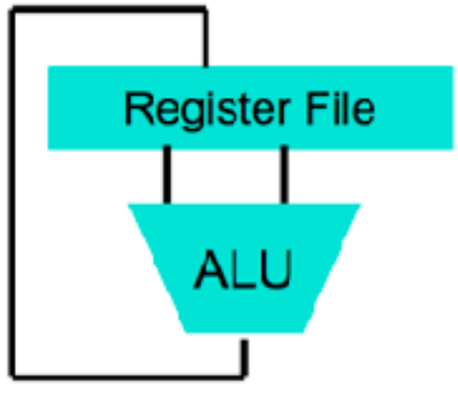
```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

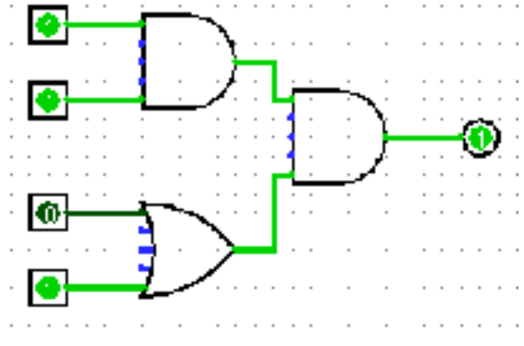
We are here!

```
lw    t0, 0(s2)
lw    t1, 4(s2)
sw    t1, 0(s2)
sw    t0, 4(s2)
```

Anything can be represented as a *number*, i.e., data or instructions

```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```





Compilation: Overview

- C compilers map C programs into architecture (OS & ISA)-specific machine code (strings of 1s and 0s)
  - Unlike Java, which converts to architecture-independent bytecode
  - Unlike Python environments, which interpret the code
  - These differ mainly in exactly when your program is converted to low-level machine instructions ("levels of interpretation")
  - For C, generally a two part process of compiling .c files to .o files, then linking the .o files into executables;
  - Assembling is also done (but is hidden, i.e., done automatically, by default); we'll talk about that later

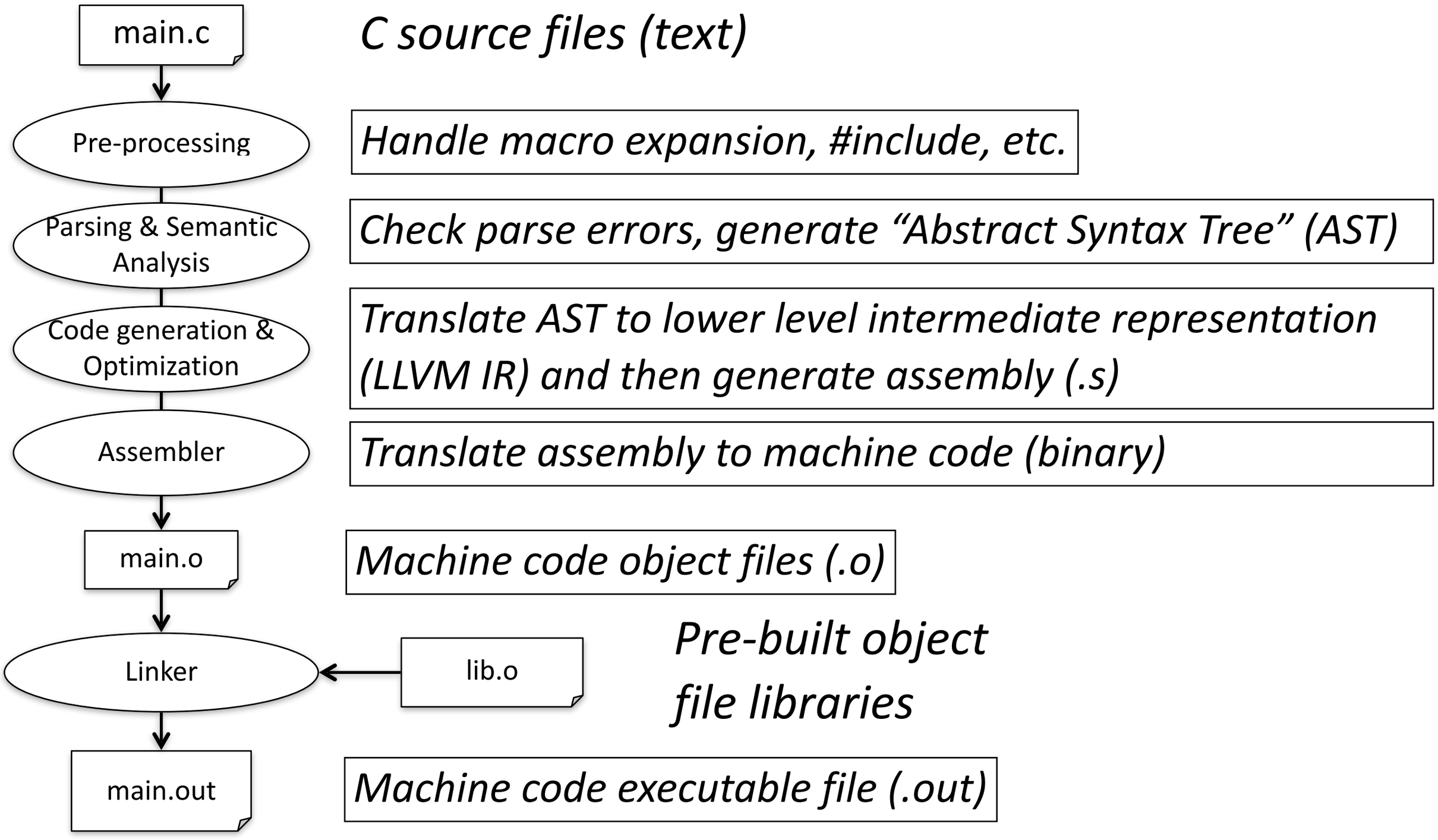
Compilation: Advantages

- Excellent run-time performance: generally much faster than Scheme or Java for comparable code (because it optimizes for a given architecture)
- Reasonable compilation time: enhancements in compilation procedure (Makefiles) allow only modified files to be recompiled

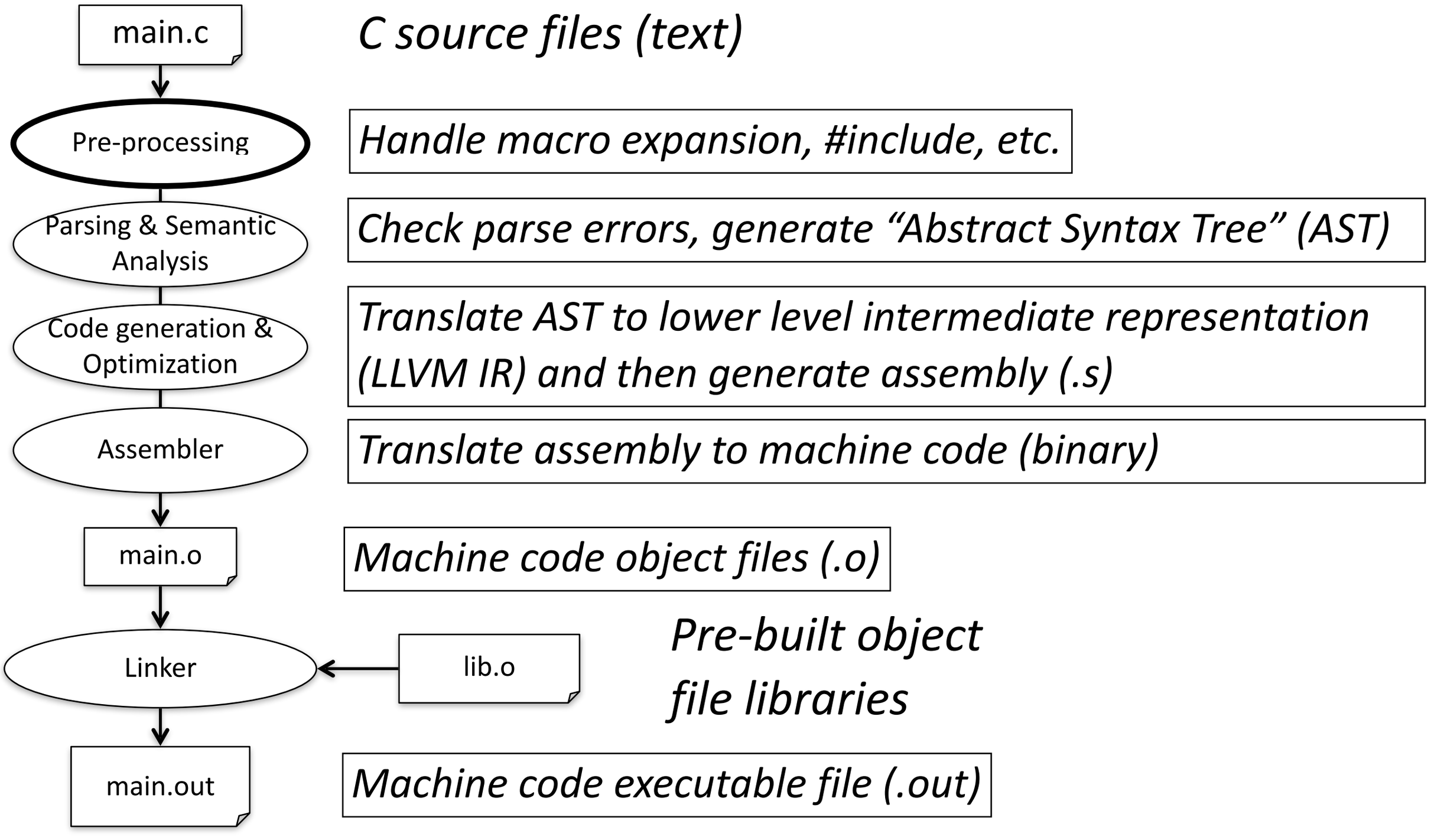
Compilation

- Mainstream C compiler in Linux:
  - GNU Complier Collection (gcc, not only for C family);
  - clang/LLVM (for C language family)
  - In terminal/command line tool/shell, “man clang/gcc”

C Compilation Simplified Overview



C Compilation Simplified Overview



C Pre-Processing (CPP)

- C source files first pass through CPP, before compiler sees code (mainly text editing)
- CPP replaces comments with a single space
- CPP commands begin with “#”
- #include “file.h” /* Inserts file.h into output */
- #include <stdio.h> /* Looks for file in standard location */
- #define M_PI (3.14159) /* Define constant */
- #if/#endif /* Conditional inclusion of text */
- Use -save-temps (-E) option to gcc to see result of preprocessing

Function-Like Macro

- #define MAG(x, y) (sqrt((x)*(x) + (y)*(y)))

```
%clang/gcc -E introC_1_0.c
```

```c
#include <stdio.h>
#include <math.h>
#define MAG0(x, y) sqrt(x*x + y*y)
#define MAG(x, y) (sqrt((x)*(x) + (y)*(y)))
#define MAG2(x,y) ({double a=x; double b=y; sqrt(a*a + b*b);})
#define MSG "Hello \
World!\n"
int main() {
#ifdef MSG
  printf(MSG /* "hi!\n" */);
#endif
    printf("%f\n",MAG(3.0,4.0));
    double i=2, j=3, k0, k1, k2, k3;
    double c=2, d=3;
    k0=MAG0(i+1,j+1);
    k1=MAG(i+1,j+1);
    k2=MAG(++i,++j);
    k3=MAG2(++c,++d);
    printf("%f\n",k0);
    printf("%f\n",k1);
    printf("%f\n",k2);
    printf("%f\n",k3);
  return 0;
}
```

=> Convention: put parenthesis EVERYWHERE!

CPP Macro II

- Avoid using macros whenever possible
- NO or very tiny speedup.
- Instead use C functions – e.g. inline function:

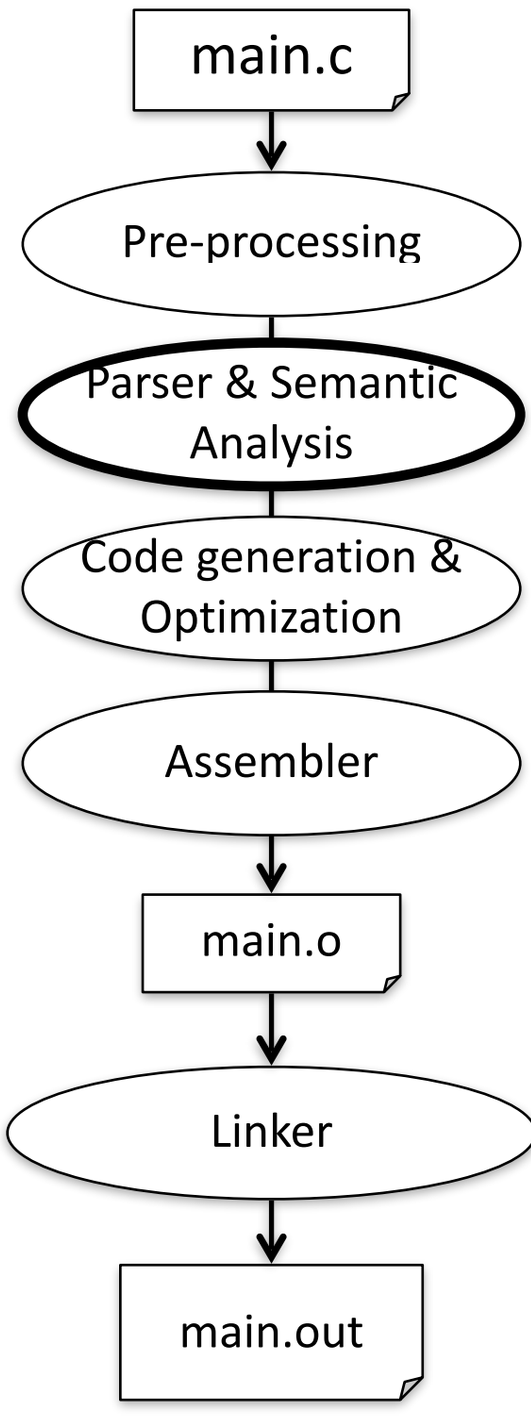
```
double mag(double x, double y);

double inline mag(double x, double y)
{  return sqrt( x*x + y*y ); }
```

Read more…

RTFM: https://gcc.gnu.org/onlinedocs/cpp/Macros.html

https://chunminchang.gitbooks.io/cplusplus-learning-note/content/Appendix/preprocessor_macros_vs_inline_functions.html

C Compilation Simplified Overview (more later in course)



C source files (text)

Handle macro expansion, #include, etc.

Check parse errors, generate "Abstract Syntax Tree" (AST)

Translate AST to lower level intermediate representation (LLVM IR) and then generate assembly (.s)

Translate assembly to machine code (binary)

Machine code object files (.o)

Pre-built object file libraries

Machine code executable file (.out)

Parser & Semantic Analysis

- Recognize each code word as a “token” (identifiers/symbols, C keywords, constant, comma, semicolon, etc.)
- Record the location of each token

```
%clang -fsyntax-only -Xclang -dump-tokens introC_1_1.c
```

```c
#include <stdio.h>
int main() {//compute 1234 + 4321
  int x = 1234, y = 4321;
  int z = x+y;
  printf("z=%d/n",z);
  return 0;
}
```

Lexer

```
int 'int'         [StartOfLine] [LeadingSpace]   Loc=<introC_1_1.c:3:3>
identifier 'x'    [LeadingSpace] Loc=<introC_1_1.c:3:7>
equal '='         [LeadingSpace] Loc=<introC_1_1.c:3:9>
numeric_constant '1234'  [LeadingSpace] Loc=<introC_1_1.c:3:11>
comma ','                 Loc=<introC_1_1.c:3:15>
identifier 'y'    [LeadingSpace] Loc=<introC_1_1.c:3:17>
equal '='         [LeadingSpace] Loc=<introC_1_1.c:3:19>
numeric_constant '4321'  [LeadingSpace] Loc=<introC_1_1.c:3:21>
semi ';'                  Loc=<introC_1_1.c:3:25>
int 'int'         [StartOfLine] [LeadingSpace]   Loc=<introC_1_1.c:4:3>
identifier 'z'    [LeadingSpace] Loc=<introC_1_1.c:4:7>
equal '='         [LeadingSpace] Loc=<introC_1_1.c:4:9>
identifier 'x'    [LeadingSpace] Loc=<introC_1_1.c:4:11>
plus '+'                  Loc=<introC_1_1.c:4:12>
identifier 'y'            Loc=<introC_1_1.c:4:13>
semi ';'                  Loc=<introC_1_1.c:4:14>
identifier 'printf'      [StartOfLine] [LeadingSpace]  Loc=<introC_1_1.c:5:3>
l_paren '('               Loc=<introC_1_1.c:5:9>
string_literal '"z=%d/n"'                Loc=<introC_1_1.c:5:10>
comma ','                 Loc=<introC_1_1.c:5:18>
identifier 'z'            Loc=<introC_1_1.c:5:19>
r_paren ')'               Loc=<introC_1_1.c:5:20>
semi ';'                  Loc=<introC_1_1.c:5:21>
return 'return'  [StartOfLine] [LeadingSpace]   Loc=<introC_1_1.c:6:3>
numeric_constant '0'     [LeadingSpace] Loc=<introC_1_1.c:6:10>
semi ';'                  Loc=<introC_1_1.c:6:11>
r_brace '}'      [StartOfLine]  Loc=<introC_1_1.c:7:1>
```

Parser & Semantic Analysis

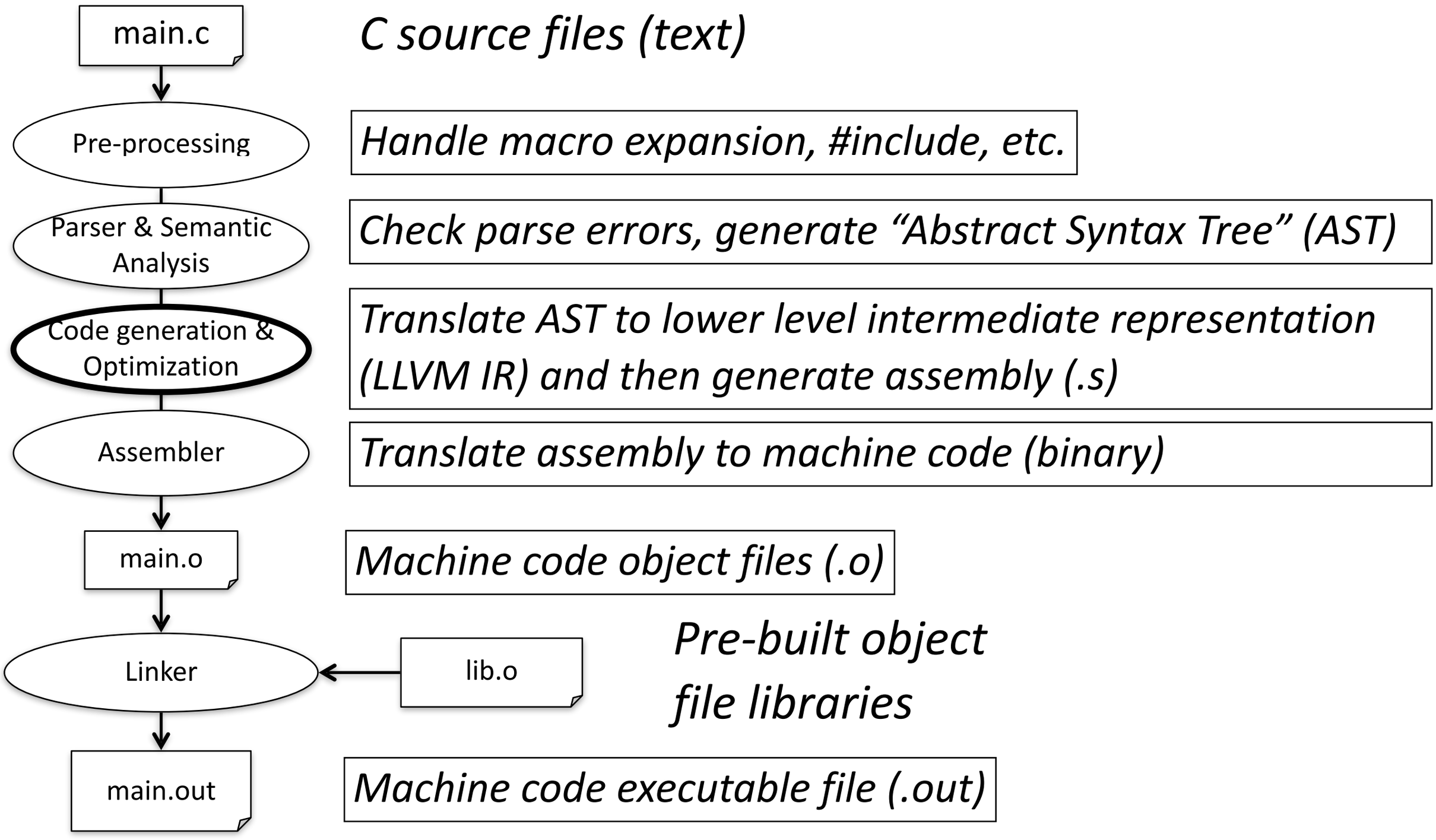
- Organize tokens as “AST” tree
- Report errors

```
% clang -fsyntax-only -Xclang -ast-dump introC_1_1.c
```

```c
#include <stdio.h>
int main() {//compute 1234 + 4321
   int x = 1234, y = 4321;
   int z = x+y;
   printf("z=%d/n",z);
   return 0;
}
```

```
`-FunctionDecl 0x1590f8600 <introC_1_1.c:2:1, line:7:1> line:2:5 main 'int ()'
  `-CompoundStmt 0x1590f8ac0 <col:12, line:7:1>
    |-DeclStmt 0x1590f87f8 <line:3:3, col:25>
    | |-VarDecl 0x1590f86b8 <col:3, col:11> col:7 used x 'int' cinit
    | | `-IntegerLiteral 0x1590f8720 <col:11> 'int' 1234
    | `-VarDecl 0x1590f8758 <col:3, col:21> col:17 used y 'int' cinit
    |   `-IntegerLiteral 0x1590f87c0 <col:21> 'int' 4321
    |-DeclStmt 0x1590f8920 <line:4:3, col:14>
    | `-VarDecl 0x1590f8828 <col:3, col:13> col:7 used z 'int' cinit
    |   `-BinaryOperator 0x1590f8900 <col:11, col:13> 'int' '+'
    |     |-ImplicitCastExpr 0x1590f88d0 <col:11> 'int' <LValueToRValue>
    |     | `-DeclRefExpr 0x1590f8890 <col:11> 'int' lvalue Var 0x1590f86b8 'x' 'int'
    |     `-ImplicitCastExpr 0x1590f88e8 <col:13> 'int' <LValueToRValue>
    |       `-DeclRefExpr 0x1590f88b0 <col:13> 'int' lvalue Var 0x1590f8758 'y' 'int'
    |-CallExpr 0x1590f89f8 <line:5:3, col:28> 'int'
    | |-ImplicitCastExpr 0x1590f89e0 <col:3> 'int (*)(const char *, ...)' <FunctionToPointerDeca
y>
    | | `-DeclRefExpr 0x1590f8938 <col:3> 'int (const char *, ...)' Function 0x1590dd388 'printf
' 'int (const char *, ...)'
```

C Compilation Simplified Overview (more later in course)



Code Generation & Optimization

- Generate intermediate representation (IR)
  - LLVM IR for clang/LLVM
  - GIMPLE for gcc

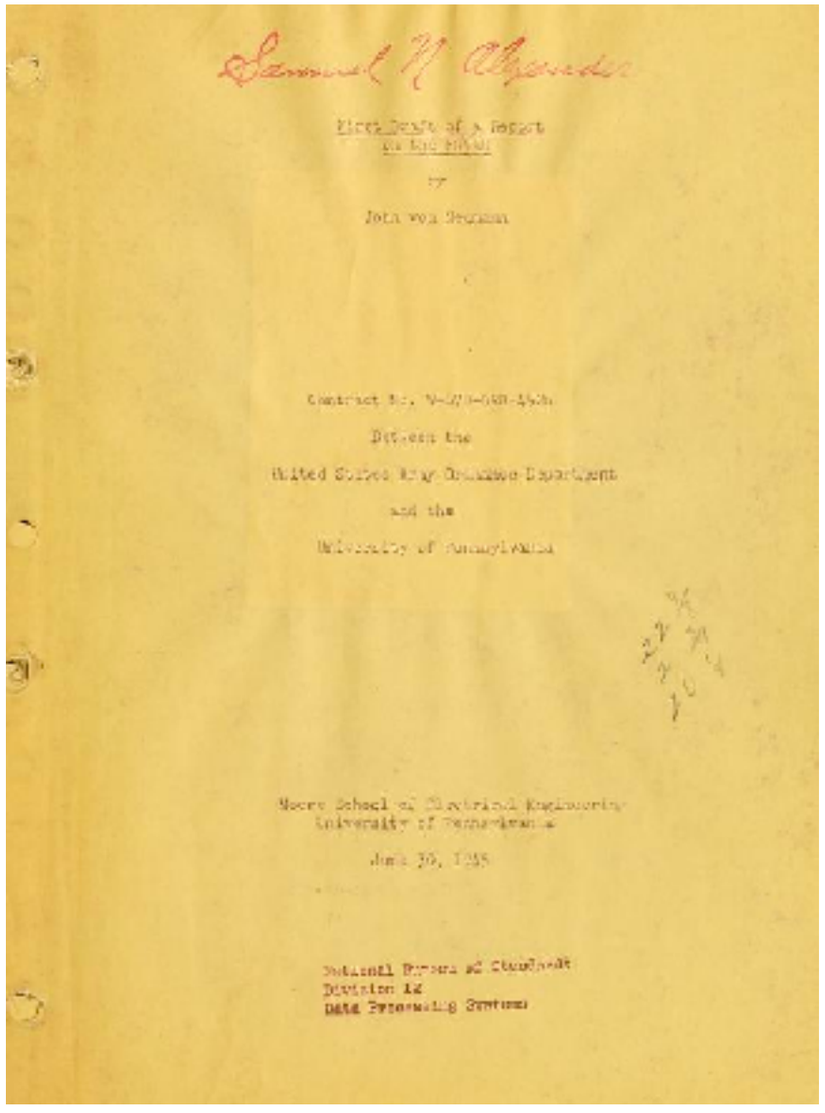
```
%clang –S –emit-llvm introC_1_1.c –o introC_1_1.ll
```

```c
#include <stdio.h>
int main() {//compute 1234 + 4321
   int x = 1234, y = 4321;
   int z = x+y;
   printf("z=%d/n",z);
   return 0;
}
```

```
; ModuleID = 'introC_1_1.c'
source_filename = "introC_1_1.c"
target datalayout = "e-m:o-i64:64-i128:128-n32:64-S128"
target triple = "arm64-apple-macosx12.0.0"

@.str = private unnamed_addr constant [7 x i8] c"z=%d/n\00", align 1

; Function Attrs: noinline nounwind optnone ssp uwtable
define i32 @main() #0 {
  %1 = alloca i32, align 4
  %2 = alloca i32, align 4
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32 0, i32* %1, align 4
  store i32 1234, i32* %2, align 4
  store i32 4321, i32* %3, align 4
  %5 = load i32, i32* %2, align 4
  %6 = load i32, i32* %3, align 4
  %7 = add nsw i32 %5, %6
  store i32 %7, i32* %4, align 4
  %8 = load i32, i32* %4, align 4
  %9 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([7 x i8]
0), i32 %8)
  ret i32 0
}
```

Components of Computers

- Von Neumann Architecture
  - *First Draft of a Report on the EDVAC*



By John von Neumann - https://archive.org/stream/firstdraftofrepooovonn#page/n1/mode/2up, Public Domain, https://commons.wikimedia.org/w/index.php?curid=26685284

Central arithmetic (CA)

Central control (CC)

Central Processing Unit (CPU)

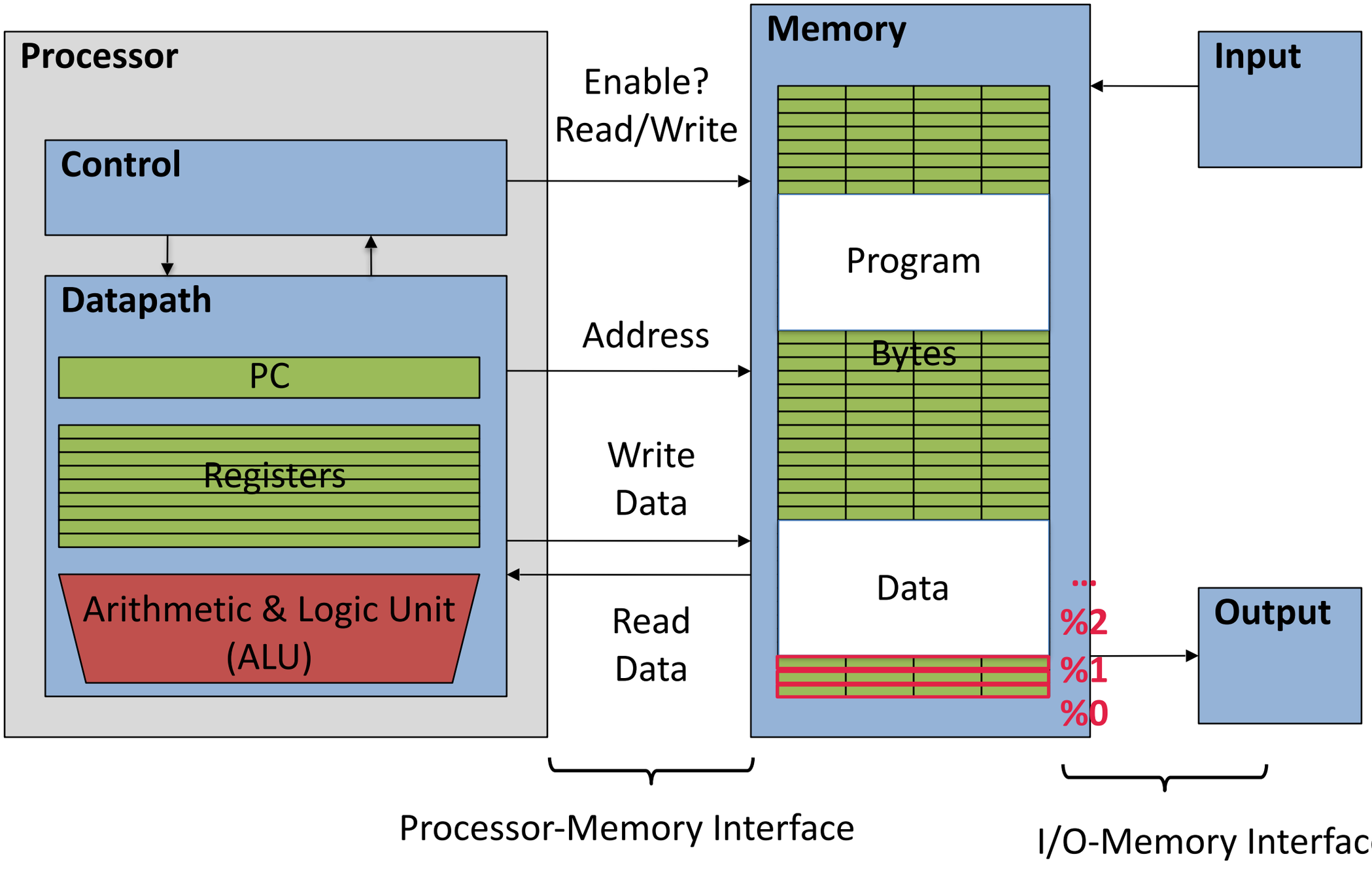
Memory (M)
(Data & Program/Instructions)

Input (I)

Output (O)

External memory (R)

Components of Computers



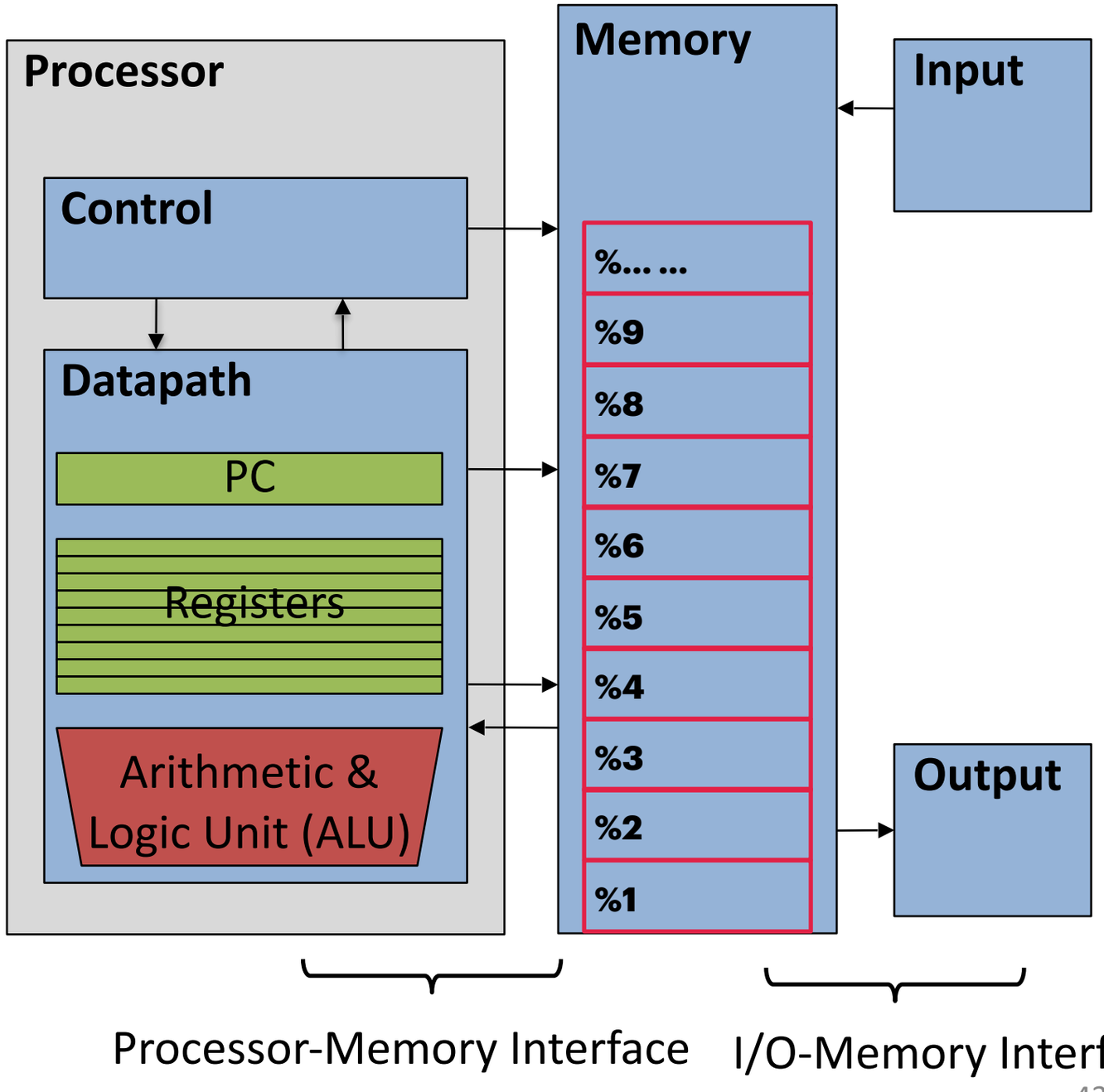
IR Implication on Hardware

```
#include <stdio.h>
int main() {//compute 1234 + 4321
  int x = 1234, y = 4321;
  int z = x+y;
  printf("z=%d/n",z);
  return 0;
}
```

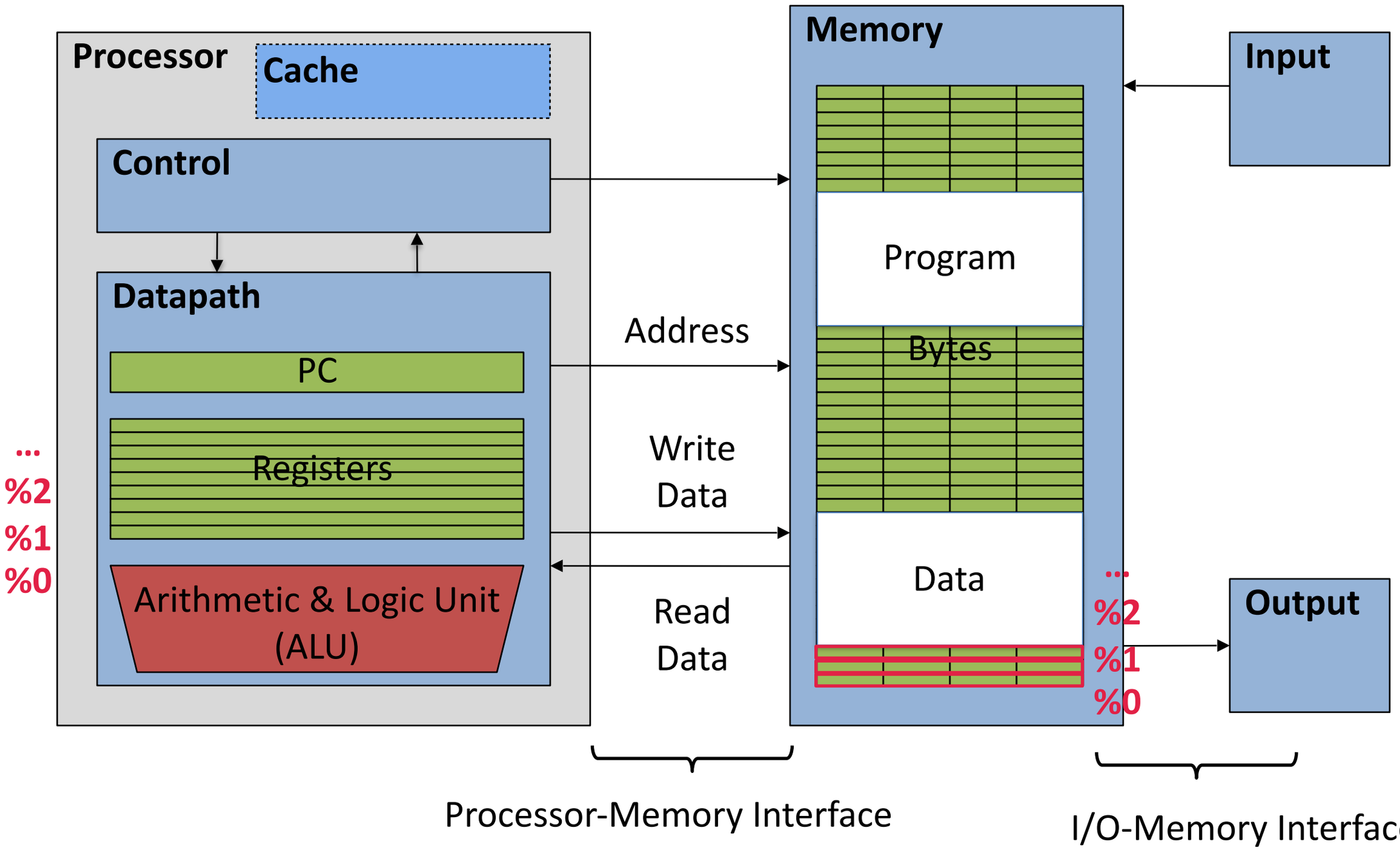
Original code

```
define i32 @main() #0 {
  %1 = alloca i32, align 4
  %2 = alloca i32, align 4
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32 0, i32* %1, align 4
  store i32 1234, i32* %2, align 4
  store i32 4321, i32* %3, align 4
  %5 = load i32, i32* %2, align 4
  %6 = load i32, i32* %3, align 4
  %7 = add nsw i32 %5, %6
  store i32 %7, i32* %4, align 4
  %8 = load i32, i32* %4, align 4
  %9 = call i32 (i8*, ...) @printf(i8*
getelementptr inbounds ([7 x i8], [7
x i8]* @.str, i64 0, i64 0), i32 %8)
  ret i32 0
}
```

LLVM IR



Optimization



IR to Assembly to Machine Code

```
% clang -S introC_1_1.c -o introC_1_1.s
```

```c
#include <stdio.h>
int main() {//compute 1234 + 4321
  int x = 1234, y = 4321;
  int z = x+y;
  printf("z=%d/n",z);
  return 0;
}
```

Original code

```
define i32 @main() #0 {
  %1 = alloca i32, align 4
  %2 = alloca i32, align 4
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32 0, i32* %1, align 4
  store i32 1234, i32* %2, align 4
  store i32 4321, i32* %3, align 4
  %5 = load i32, i32* %2, align 4
  %6 = load i32, i32* %3, align 4
  %7 = add nsw i32 %5, %6
  store i32 %7, i32* %4, align 4
  %8 = load i32, i32* %4, align 4
  %9 = call i32 (i8*, ...) @printf(i8*
getelementptr inbounds ([7 x i8], [7 x i8]*
@.str, i64 0, i64 0), i32 %8)
  ret i32 0
}
```

LLVM IR

```
    .section __TEXT,__text,regular,pure_instructions
    .build_version macos, 12, 0    sdk_version 13, 1
    .globl   _main                          ; -- Begin function
main
    .p2align 2
_main:                                      ; @main
    .cfi_startproc
; %bb.0:
    sub  sp, sp, #48
    stp  x29, x30, [sp, #32]            ; 16-byte Folded Spill
    add  x29, sp, #32
    .cfi_def_cfa w29, 16
    .cfi_offset w30, -8
    .cfi_offset w29, -16
    mov  w8, #0
    str  w8, [sp, #12]                      ; 4-byte Folded Spill
    sturwzr, [x29, #-4]
    mov  w8, #1234
    sturw8, [x29, #-8]
    mov  w8, #4321
    sturw8, [x29, #-12]
    ldurw8, [x29, #-8]
    ldurw9, [x29, #-12]
    add  w8, w8, w9
    str  w8, [sp, #16]
    ldr  w9, [sp, #16]
```

ARM Assembly

Translated to machine code defined by ISA

IR to Assembly to Machine Code

```
% clang -c introC_1_1.c -o introC_1_1.o
% objdump -d introC_1_1.o
```

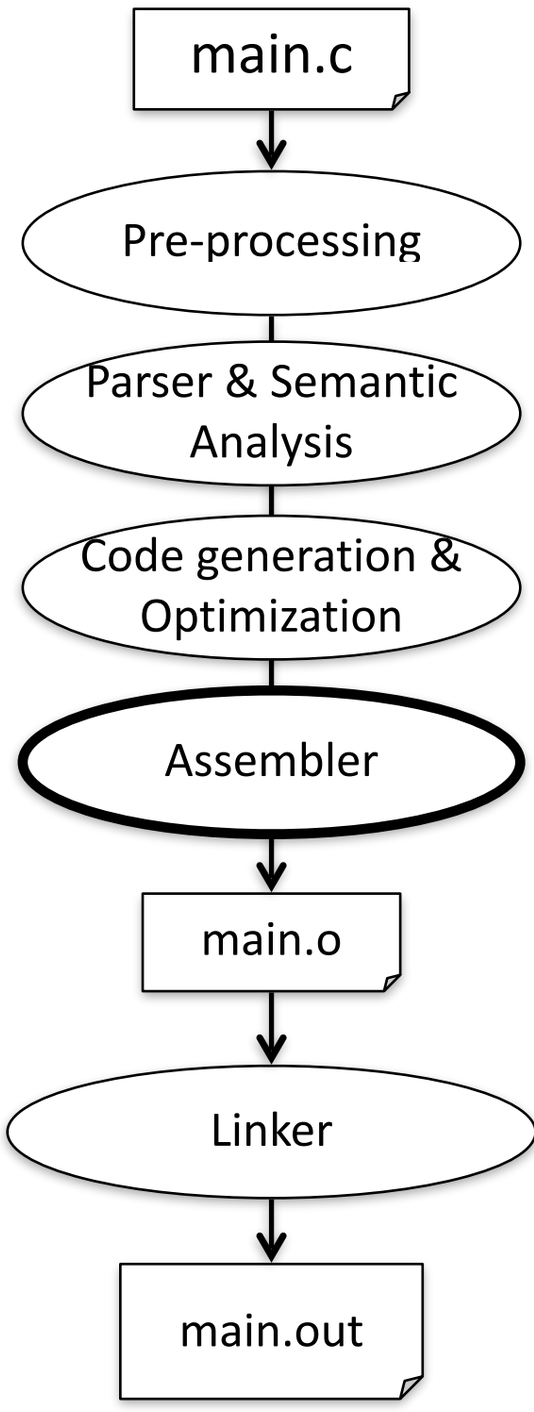
Machine Code

(Stored program/ instructions)

```
Disassembly of section __TEXT,__text:

0000000000000000 <ltmp0>:
       0: ff c3 00 d1   sub sp, sp, #48
       4: fd 7b 02 a9   stp x29, x30, [sp, #32]
       8: fd 83 00 91   add x29, sp, #32
       c: 08 00 80 52   mov w8, #0
      10: e8 0f 00 b9   str w8, [sp, #12]
      14: bf c3 1f b8   stur wzr, [x29, #-4]
      18: 48 9a 80 52   mov w8, #1234
      1c: a8 83 1f b8   stur w8, [x29, #-8]
      20: 28 1c 82 52   mov w8, #4321
      24: a8 43 1f b8   stur w8, [x29, #-12]
      28: a8 83 5f b8   ldur w8, [x29, #-8]
      2c: a9 43 5f b8   ldur w9, [x29, #-12]
      30: 08 01 09 0b   add w8, w8, w9
      34: e8 13 00 b9   str w8, [sp, #16]
      38: e9 13 40 b9   ldr w9, [sp, #16]
      3c: e8 03 09 aa   mov x8, x9
      40: e9 03 00 91   mov x9, sp
      44: 28 01 00 f9   str x8, [x9]
      48: 00 00 00 90   adrp x0, 0x0 <ltmp0+0x48>
      4c: 00 00 00 91   add x0, x0, #0
      50: 00 00 00 94   bl 0x50 <ltmp0+0x50>
      54: e0 0f 40 b9   ldr w0, [sp, #12]
      58: fd 7b 42 a9   ldp x29, x30, [sp, #32]
      5c: ff c3 00 91   add sp, sp, #48
      60: c0 03 5f d6   ret
```

ARM Assembly

C Compilation Simplified Overview



C source files (text)

Handle macro expansion, #include, etc.

Check parse errors, generate "Abstract Syntax Tree" (AST)

Translate AST to lower level intermediate representation (LLVM IR) and then generate assembly (.s)

Translate assembly to machine code (binary, .o)

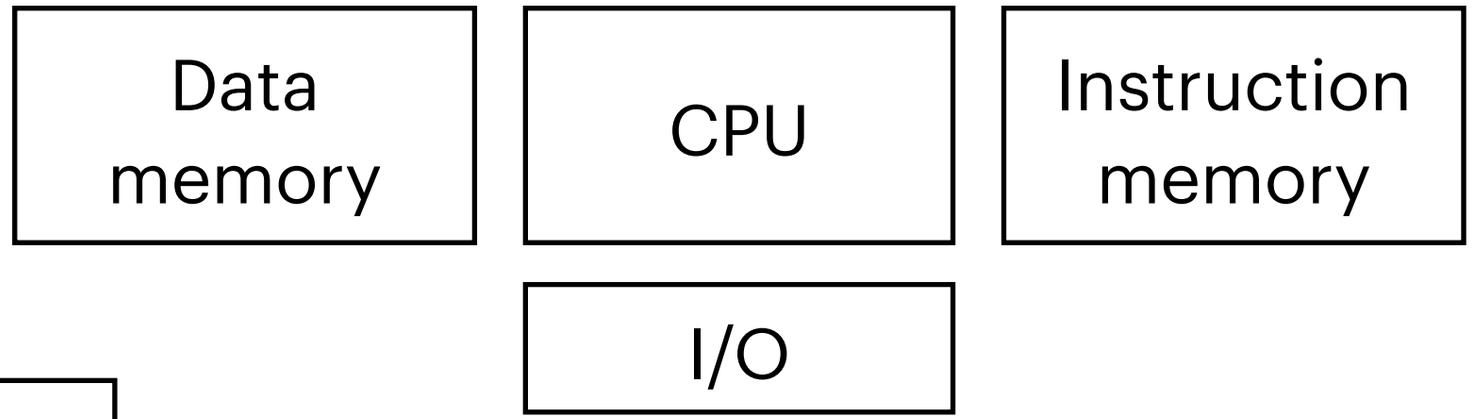
Machine code object files (.o)

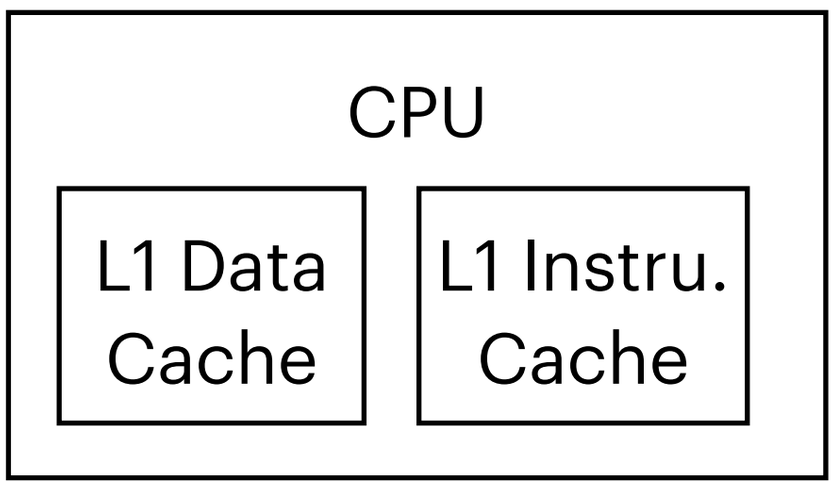
Pre-built object file libraries

Machine code executable file (.out)

Organization of Computers

- Von Neumann Architecture
  - a.k.a. Princeton architecture
  - Uniform memory for data & program/instruction
- Harvard Architecture
  - Separated memory for data & program
  - E.g. MCU, DSP, L1 Cache



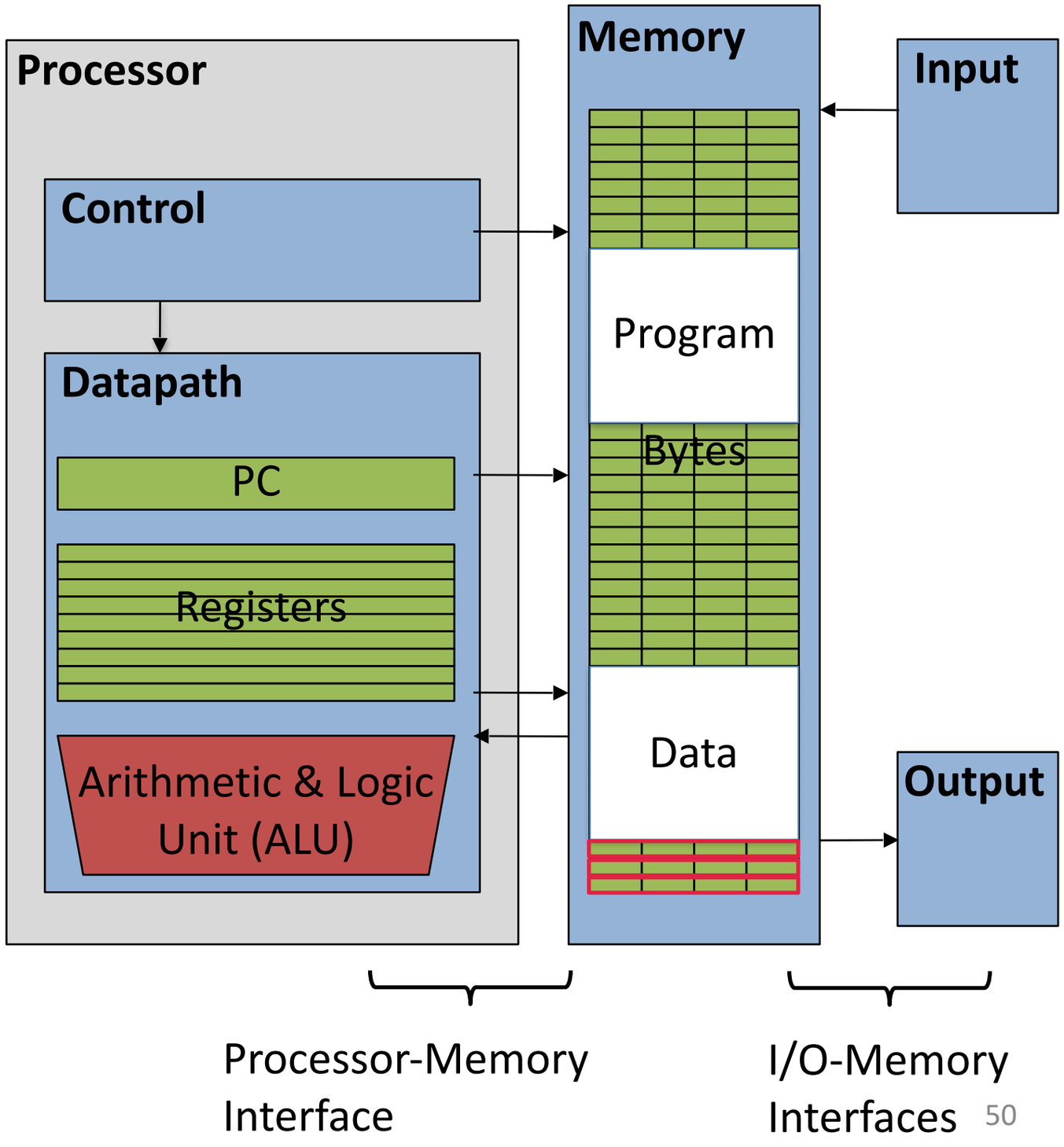


Wrap-it-up

- From C to machine code (clang *.c → *.out & ./*.out)
  - Pre-processing (macro, function-like macro, text editing, #include)
    - Use "()" whenever necessary, or use "function" directly
  - Parser & Semantic Analysis (tokenization & generate AST, basic operations)
  - Translate to IR & optimize (computer components)
  - Translate to assembly and then machine code, executed by hardware (**Covered in future lectures**)
  - Clang manual: https://releases.llvm.org/14.0.0/tools/clang/docs/UsersManual.html
  - GCC: https://gcc.gnu.org/

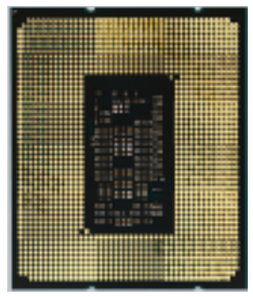
Wrap-it-up

- Von Neumann Architecture
- Harvard Architecture
- Stored-program computer



Real Stuff

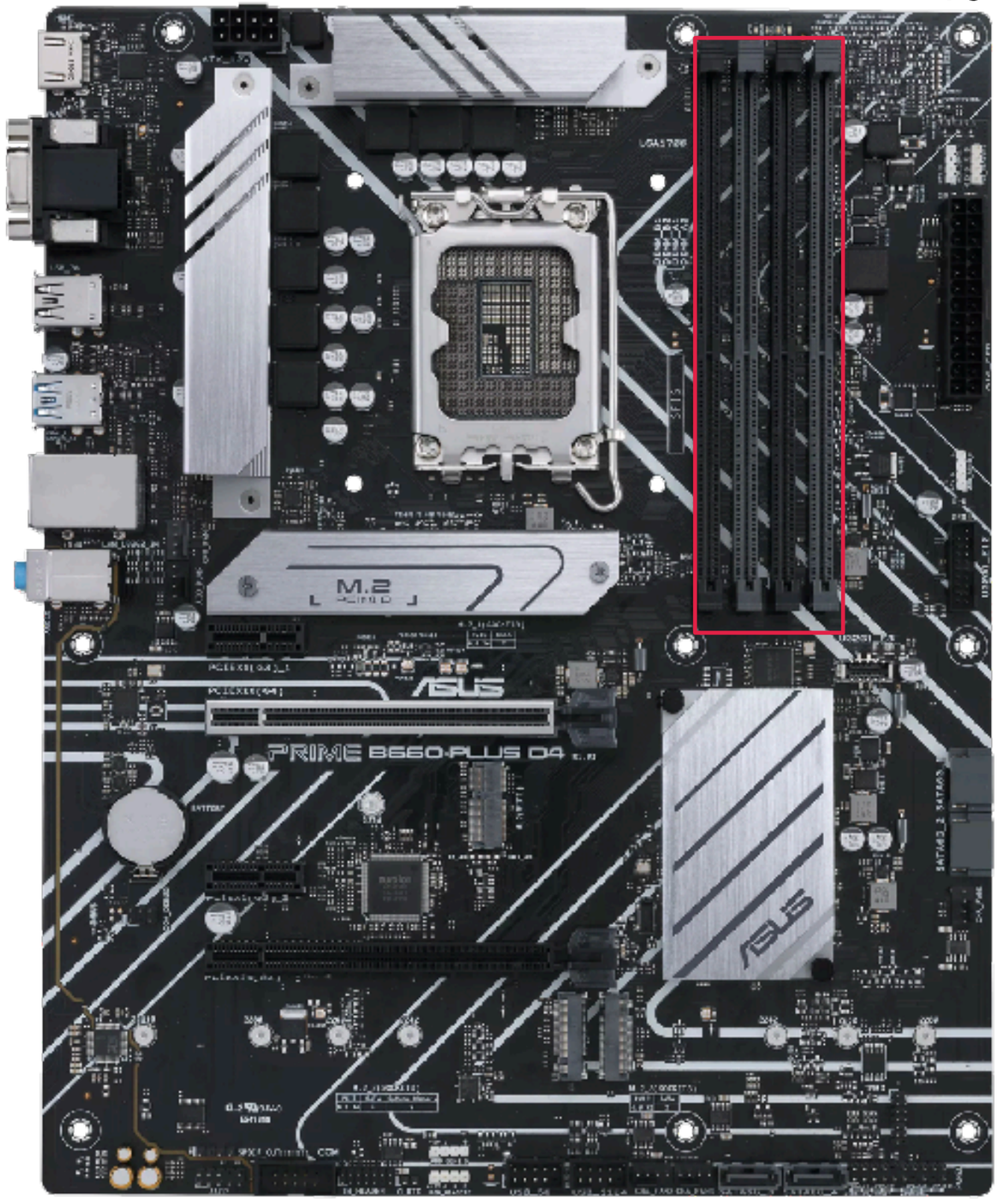
Intel i7 12700 4.90 GHz



https://maj191.com/product/intel-core-i7-12700-3-6ghz-cpu-25mb-cache-lga1700-tray/

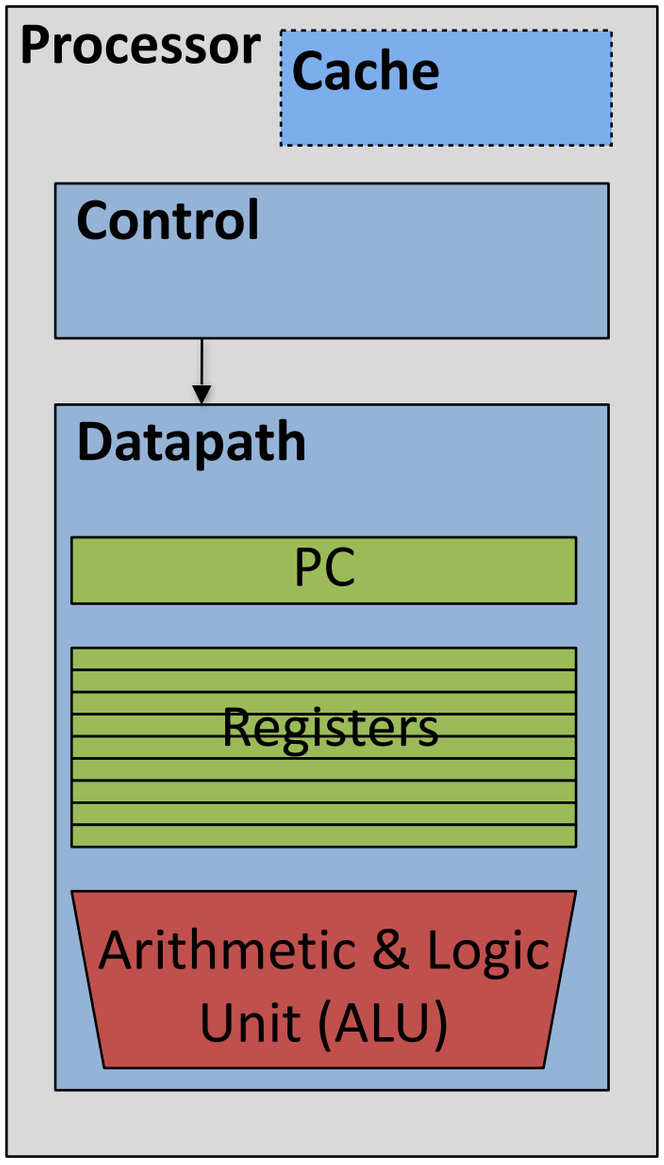
https://www.ocinside.de/review/intel_core_i7_12700k/3/

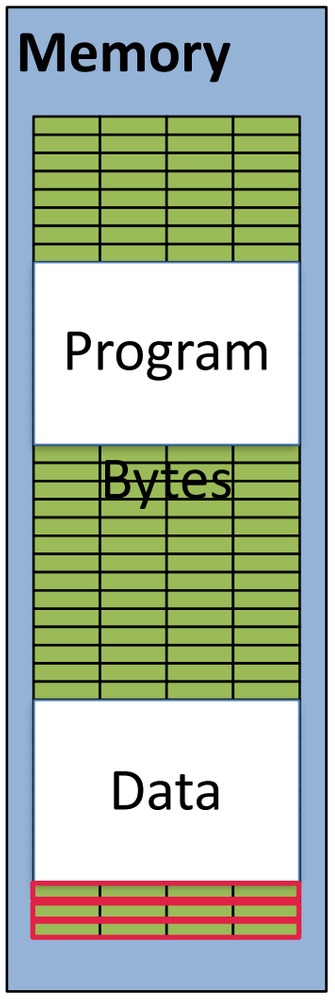
DIMM DDR4 5066 MHz



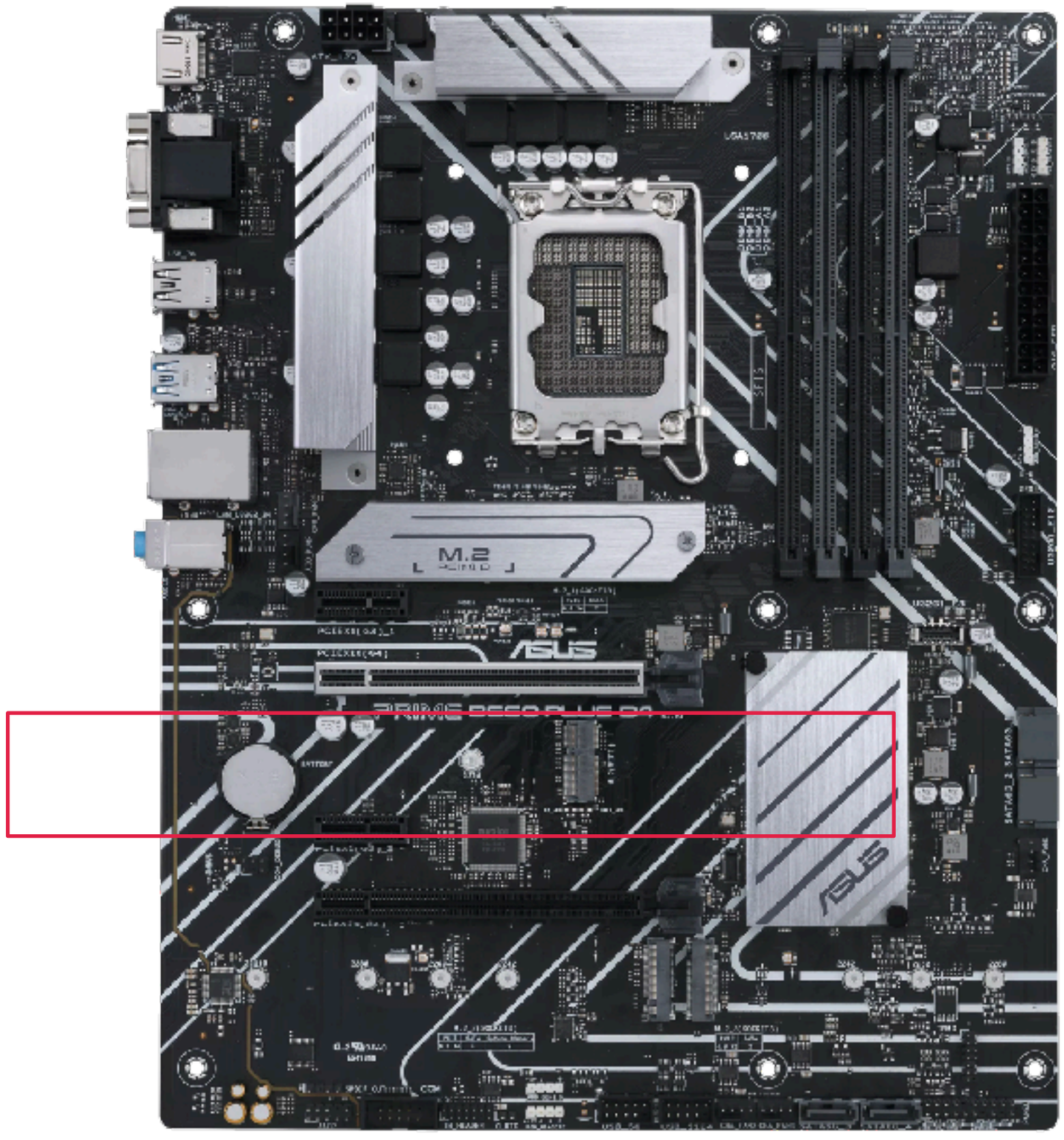
Kingston
8/16/32G
SDRAM

https://www.asus.com/motherboards-components/motherboards/prime/prime-b660-plus-d4/





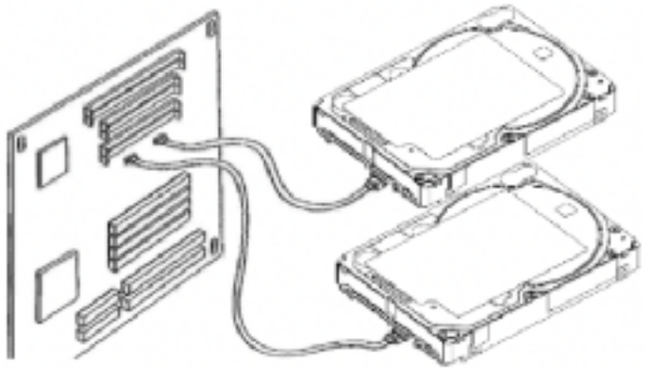
Real Stuff

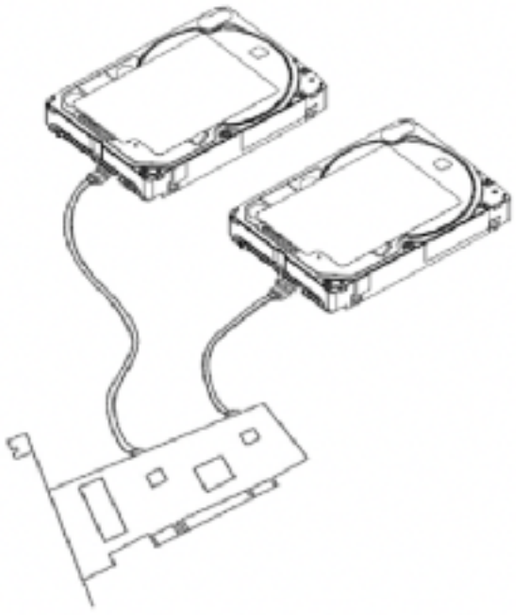


https://www.asus.com/motherboards-components/motherboards/prime/prime-b660-plus-d4/

Real Stuff

SSD vs. HDD



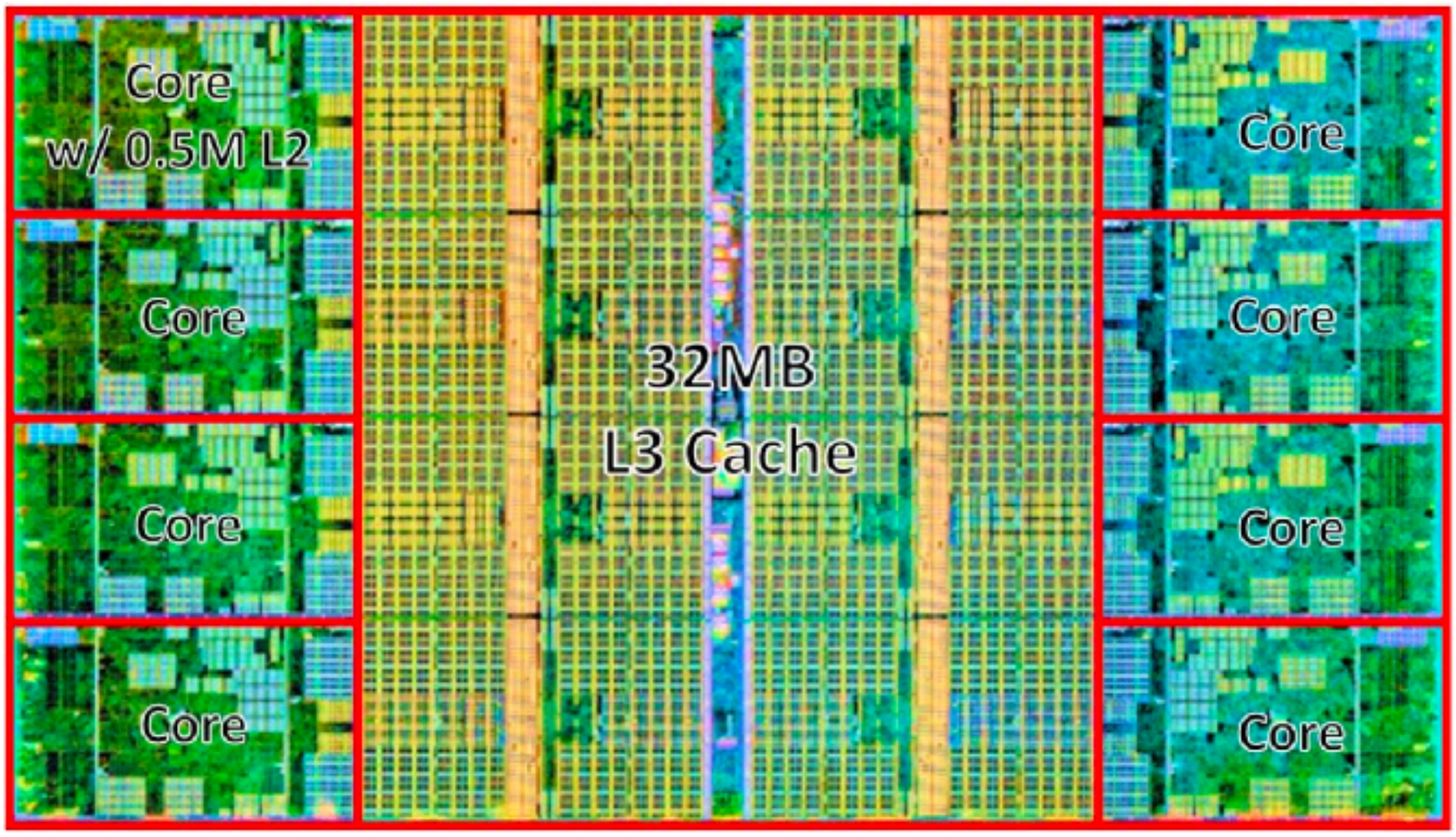


From Seagate

https://www.samsung.com/us/computing/memory-storage/solid-state-drives/ssd-970-pro-nvme-m2-512gb-mz-v7p512bw/
https://www.seagate.com/in/en/products/hard-drives/barracuda-hard-drive/

Real Stuff— Inside a CPU

AMD Zen 3 8-core CPU, 7 nm process, 4.08B transistors in 68 mm²



T. Burd *et al.*, "Zen3: The AMD 2nd-Generation 7nm x86-64 Microprocessor Core," *2022 IEEE International Solid- State Circuits Conference (ISSCC)*, San Francisco, CA, USA, 2022, pp. 1-3.

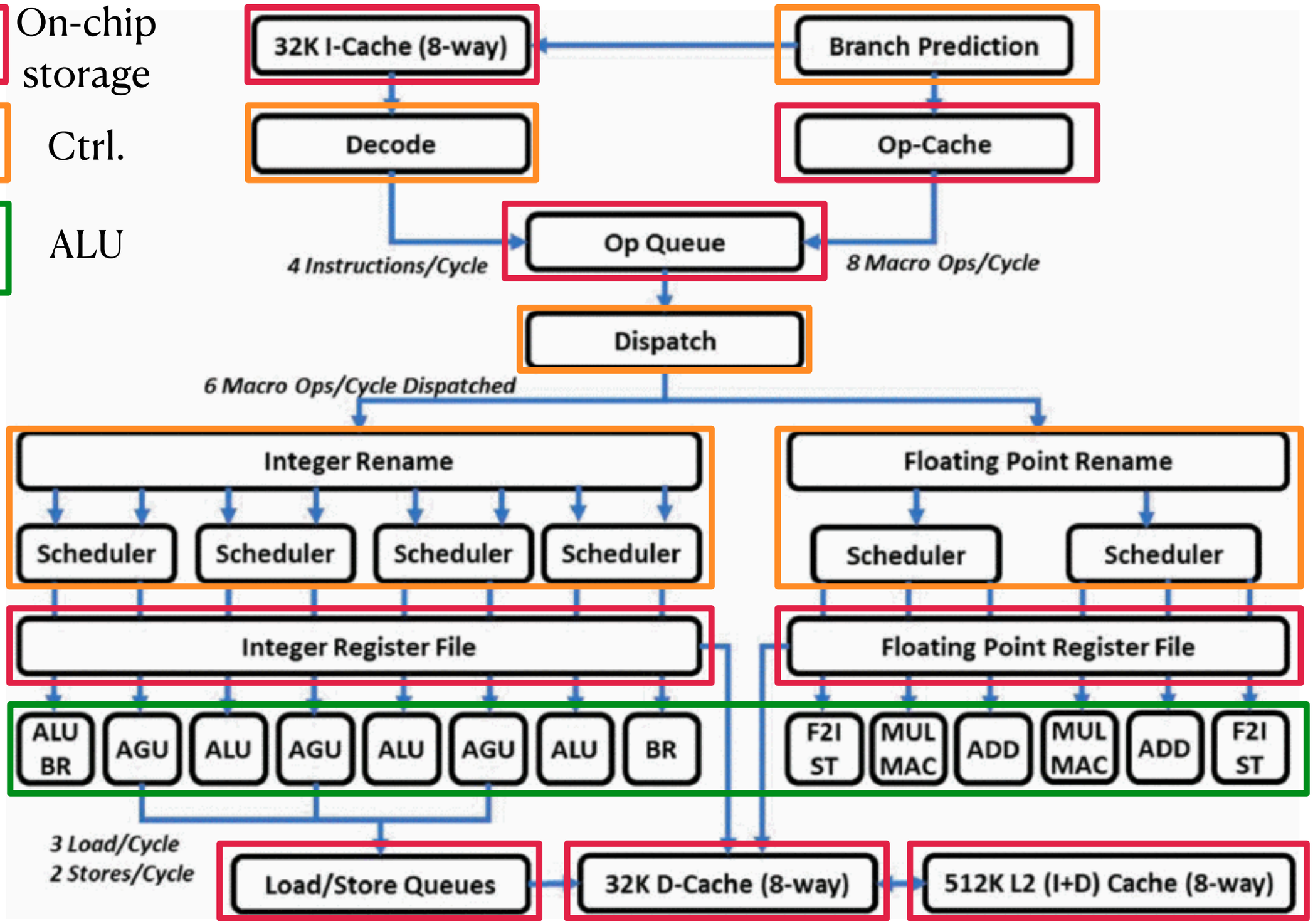
Real Stuff— Inside a CPU

AMD Zen 3, 7 nm process, a single core

On-chip storage

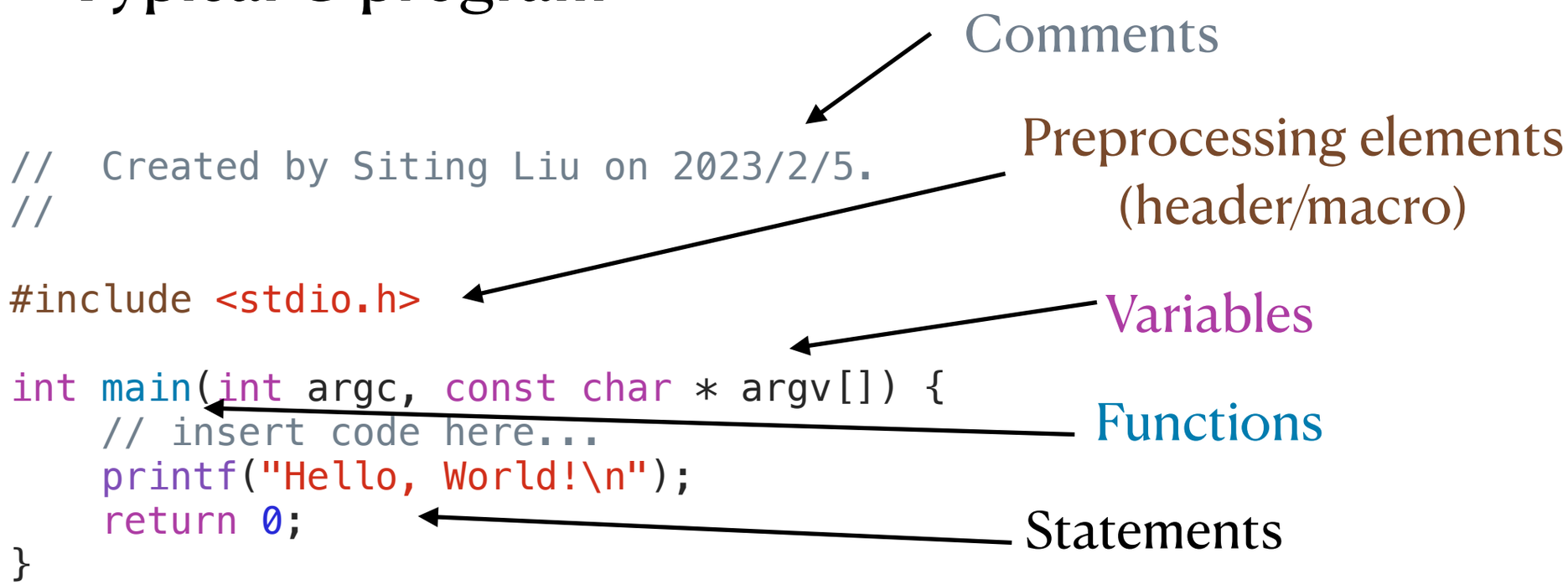
Ctrl.

ALU



Back to C

- Typical C program




```c
//  Created by Siting Liu on 2023/2/5.
//

#include <stdio.h>

int main(int argc, const char * argv[]) {
    // insert code here...
    printf("Hello, World!\n");
    return 0;
}
```

- Must C program start with main()? (RTFM/C standard)

Variables

- Typed Variables in C

```
int    variable1    = 2;
float  variable2    = 1.618;
char   variable3    = 'A';
```

Must declare the type of data a variable will hold

Type	Description	Examples
int	integer numbers, including negatives	0, 78, -1400
unsigned int	integer numbers (no negatives)	0, 46, 900
long	larger signed integer	-6,000,000,000
(un)signed char	single text character or symbol	'a', 'D', '?’
float	floating point decimal numbers	0.0, 1.618, -1.4
double	greater precision/big FP number	10E100

Integers

- Typed Variables in C

Language	sizeof(int)
Python	>=32 bits (plain ints), infinite (long ints)
Java	32 bits
C	Depends on computer; 16 or 32 or 64 bits

- C: int should be integer type that target processor works with most efficiently
- Generally: sizeof(long long) ≥ sizeof(long) ≥ sizeof(int) ≥ sizeof(short)
  - Also, short >= 16 bits, long >= 32 bits
  - All could be 64 bits

Integer Constants

```c
#include <stdio.h>
int main() {
   printf((6-2147483648)>(6)?"T\n":"F\n");
   printf((6-0x80000000)>(6)?"T\n":"F\n");
   return 0;
}
```

Semantics: The value of a decimal constant is computed base 10; that of an octal constant base 8; that of a hexadecimal constant base 16. The lexically first digit is the most significant.
The type of an integer constant is the first of the corresponding list in which its value can be represented. Unsuffixed decimal **int, long int, unsigned long int;** unsuffixed octal or hexadecimal: **int, unsigned int, long int, unsigned long int;** suffixed by the letter u or U: **unsigned int, unsigned long int**; suffixed by the letter l or L: **long int, unsigned long int**; suffixed by both the letters u or U and 1 or L: **unsigned long int**.

Range of each type defined in <`limits.h`> (INT_MAX, INT_MIN)

Consts. and Enums. in C

- Constant is assigned a typed value once in the declaration; value can't change during entire execution of program

```
const float golden_ratio = 1.618;
const int days_in_week = 7;
```

- You can have a constant version of any of the standard C variable types
- Enums: a group of related integer constants. Ex:

```
enum cardsuit {CLUBS,DIAMONDS,HEARTS,SPADES};
enum color {RED, GREEN, BLUE};
```

Compare "`#define PI 3.14`" and "`const float pi=3.14`" – which is true?

A: Constants "PI" and "pi" have same type

B: Can assign to "PI" but not "pi"

C: Code runs at about the same speed using "PI" or "pi"

D: "pi" takes more memory space than "PI"

E: Both behave the same in all situations

C Syntax: Variable Declarations

- All variable declarations must appear before they are used (e.g., at the beginning of the block)
- A variable may be initialized in its declaration;
  if not, it holds garbage!
- Examples of declarations:
  - Correct: {

```
int a = 0, b = 10;
...
```

  - Incorrect: `for (int i = 0; i < 10; i++)`

```
}
```

Newer C standards are more flexible about this…

C Syntax: True or False

- What evaluates to FALSE in C?
  - 0 (integer)
  - NULL (a special kind of pointer: more on this later)
- No explicit Boolean type
- What evaluates to TRUE in C?
  - Anything that isn't false is true
  - Same idea as in Python: only 0s or empty sequences are false, anything else is true!

C operators

- arithmetic: +, -, *, /, %
- assignment: =
- augmented assignment: +=, -=, *=, /=, %=, &=, |=, ^=, <<=, >>=
- bitwise logic: ~, &, |, ^
- bitwise shifts: <<, >>
- boolean logic: !, &&, ||
- equality testing: ==, !=
- subexpression grouping: ( )
- order relations: <, <=, >, >=
- increment and decrement: ++ and --
- member selection: ., ->
- conditional evaluation: ? :

Summary

- C preprocessing
- C variables
- C operators