CSC 212: Data Structures and Abstractions

02: C++ Review, Memory, and Pointers

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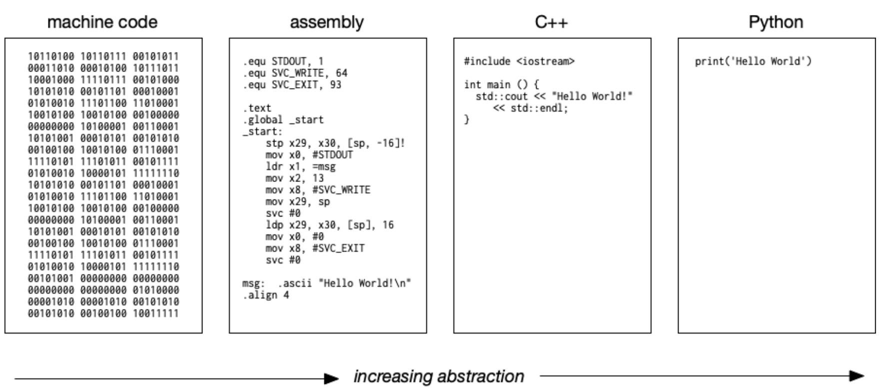
THINK BIG WE DO℠

Compiling C++ programs

Context



To illustrate the potential gains from performance engineering, consider multiplying two 4096-by-4096 matrices. Here is the four-line kernel of Python code for matrix-multiplication:

```
for i in xrange(4096):
    for j in xrange(4096):
        for k in xrange(4096):
            C[i][j] += A[i][k] * B[k][j]
```

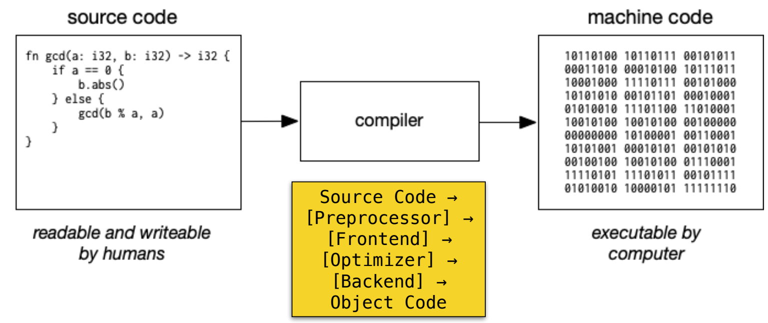
Version	Implementation	Running time (s)	GFLOPS	Absolute speedup	Relative speedup	Fraction of peak (%)
1	Python	25,552.48	0.005	1	—	0.00
2	Java	2,372.68	0.058	11	10.8	0.01
3	C	542.67	0.253	47	4.4	0.03
4	Parallel loops	69.80	1.969	366	7.8	0.24
5	Parallel divide and conquer	3.80	36.180	6,727	18.4	4.33
6	plus vectorization	1.10	124.914	23,224	3.5	14.96
7	plus AVX intrinsics	0.41	337.812	62,806	2.7	40.45

Program execution approaches

- Compilation
  - ✓ high level source **translated** into another language
    - often into a machine-specific instructions
    - translation occurs through multiple phases
  - ✓ compilers can perform **optimizations** to make the code more efficient, resulting in faster execution (higher performance)
  - ✓ e.g. C/C++ compilers
- Interpretation
  - ✓ "executing" a program directly from source
    - read code line by line, translate it into machine code, and execute
    - any language can be interpreted
  - ✓ preferred when performance is not critical
  - ✓ e.g. Javascript

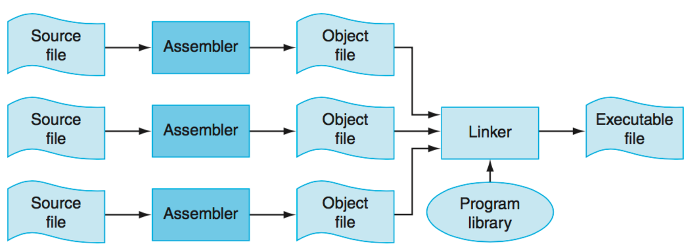
Compiling programs (simplified)

- Typically, "compiling" a program refers to the process of generating machine code from source code
  - ✓ the process takes several steps: compile, assemble, link



https://www.uvm.edu/~cbcafier/cs1210/book/02_programming_and_the_python_shell/programming.html

Compiling/linking/running C programs




```
C++ programs can be compiled/linked through both IDEs and command-line tools.

• Command Line: Using compilers like g++ or clang++ gives you fine-grained
  control.

• IDE: IDEs like VS Code, Code::Blocks, or CLion handle compilation/linking behind
  the scenes. They typically use build systems like CMake, Make to manage the
  process automatically.

The command line gives you transparency and scriptability - you can see exactly
what flags are being used and automate builds easily. IDEs provide convenience,
debugging integration, and often better error visualization, but can sometimes
obscure what's actually happening during the build process.
```

From Computer Organization and Computer Design: The Hardware/Software Interface

Data representation

Range of values

Data type	Size	Format	Value range
character	8	signed	−128 to 127
		unsigned	0 to 255
integer	16	signed	−32768 to 32767
		unsigned	0 to 65535
	32	signed	−2,147,483,648 to 2,147,483,647
		unsigned	0 to 4,294,967,295
	64	signed	−9,223,372,036,854,775,808 to 9,223,372,036,854,775,807
		unsigned	0 to 18,446,744,073,709,551,615

Data type	Smallest positive value (*)	Largest positive value (*)	Precision (**)
float	$\sim 1.401 \cdot 10^{-45}$	$\sim 3.403 \cdot 10^{+38}$	6-9 digits
double	$\sim 4.941 \cdot 10^{-324}$	$\sim 1.798 \cdot 10^{+308}$	15-17 digits

https://en.cppreference.com/w/cpp/language/types

Standard integer types

Type specifier	Equivalent type	Width in bits by data model				
		C++ standard	LP32	ILP32	LLP64	LP64
`signed char`	`signed char`	at least 8	8	8	8	8
`unsigned char`	`unsigned char`					
`short`	`short int`	at least 16	16	16	16	16
`short int`						
`signed short`						
`signed short int`						
`unsigned short`	`unsigned short int`					
`unsigned short int`						
`int`	`int`	at least 16	16	32	32	32
`signed`						
`signed int`						
`unsigned`	`unsigned int`					
`unsigned int`						
`long`	`long int`	at least 32	32	32	32	64
`long int`						
`signed long`						
`signed long int`						
`unsigned long`	`unsigned long int`					
`unsigned long int`						
`long long`	`long long int` (C++11)	at least 64	64	64	64	64
`long long int`						
`signed long long`						
`signed long long int`						
`unsigned long long`	`unsigned long long int` (C++11)					
`unsigned long long int`						

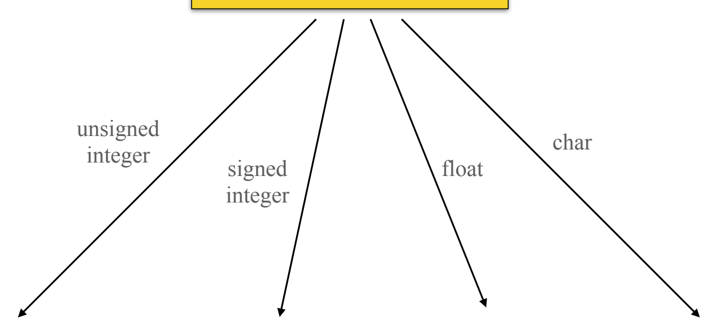
What is the output?

```
#include <iostream>

int main() {
    int d = 42;
    int o = 052;
    int x = 0x2a;
    int X = 0X2A;
    int b = 0b101010; // C++14

    std::cout << d << " " << o << " " << x
        << " " << X << " " << b << std::endl;

    return 0;
}
```


Variables are just bit sequences

`1000 1110 0011 0001 0011 0001 0011 0100`

0x8E313134



2385588532 −1909378764 −2.1841e−30f “411?”

Memory and pointers

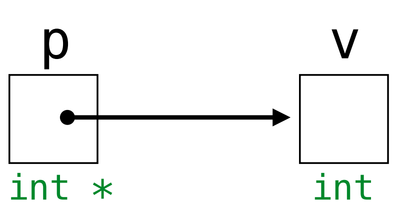
Memory organization

- Memory as a byte array
  - contiguous sequence of bytes
  - used to store **data and instructions** for computer programs
  - each byte individually accessed via a **unique address**
- Memory address
  - **unique** numerical identifier for each byte in memory, often displayed in hexadecimal notation
  - provides indirect access to data stored at that location
- Data representation in memory
  - variables stored as byte sequences
  - interpretation and number of bytes depends on type
    - integers, floating-point numbers, characters, etc.

Variables and pointers

- Every variable exists at a **memory address**
  - regardless of **variable scope**
  - the compiler translates names to addresses when generating machine code

`A pointer is just a variable that stores the memory address of another variable`



Pointers

- Declaration
  - like other variables, pointers must be declared before use
  - for each declaration, a pointer type must be specified

```
type *pointer_name;
```

- Pointer operators
  - **address-of** operator: get memory address of variable/object

`&`

  - **dereference** operator: get value at given memory address

`*`

Declaring pointers

```
// can declare a single
// pointer (preferred)
int *p;

// can declare multiple
// pointers of the same type
int *p1, *p2;

// can declare pointers
// and other variables too
double *p3, var, *p4;
```


Pointer operators

```
int main() {
    int var = 10;
    int *ptr;
    ptr = &var;
    *ptr = 20;

    // ...

    return 0;
}
```

32-bit words

Address	Value	Variable
…		
0x91340A08		
0x91340A0C		
0x91340A10		
0x91340A14		
0x91340A18		
0x91340A1C		
0x91340A20		
0x91340A24		
0x91340A28		
0x91340A2C		
0x91340A30		
0x91340A34		
…		

Pointer operators

```
int main() {
    int temp = 10;
    int value = 100;
    int *p1, *p2;

    p1 = &temp;
    *p1 += 10;

    p2 = &value;
    *p2 += 5;

    p2 = p1;
    *p2 += 5;

    return 0;
}
```

32-bit words

Address	Value	Variable
…		
0x91340A08		
0x91340A0C		
0x91340A10		
0x91340A14		
0x91340A18		
0x91340A1C		
0x91340A20		
0x91340A24		
0x91340A28		
0x91340A2C		
0x91340A30		
0x91340A34		
…		

Pointers and functions

```
void increment(int *ptr) {
    (*ptr) ++;
}

int main() {
    int var = 10;

    increment(&var);
    increment(&var);

    // ...

    return 0;
}
```

32-bit words

Address	Value	Variable
…		
0x91340A08		
0x91340A0C		
0x91340A10		
0x91340A14		
0x91340A18		
0x91340A1C		
0x91340A20		
0x91340A24		
0x91340A28		
0x91340A2C		
0x91340A30		
0x91340A34		
…		

Pointer arithmetic

- Core principle
  - ✓ allows mathematical operations (**addition, subtraction**) with pointers, but works differently than regular arithmetic
- Key Rules
  - ✓ add/subtract integer values to pointers (`p + n`)
    - adding `n` to a pointer `p` moves it forward by (`n * sizeof(*p)`) bytes
  - ✓ memory addresses are integers, typically displayed in hexadecimal format

Warning: adding 1 to a pointer means moving to the next element of the pointed-to type, not moving 1 byte forward in memory

- incorrect pointer arithmetic can lead to buffer overflows and undefined behavior
- always verify pointer bounds before arithmetic operations

Pointer arithmetic

```
int arr[] = {1, 2, 3, 4, 5};
int *ptr = arr;
ptr ++;    // advances ptr by 4 bytes
ptr += 2; // advances ptr by 8 bytes
```

Note: an **array name** is NOT a pointer variable but an immutable array identifier that automatically converts to a pointer in most contexts. In expressions and function calls, arr undergoes "pointer decay" and behaves as &arr[0].

Example: changing a pointer within a function

```
#include <iostream>

void seek(int *p, int key, int n) {
    for (int i = 0 ; i < n; i++) {
        if (*p == key) {
            return;
        }
        p ++;
    }
}

int main() {
    int data[] = {1, 2, 3, 4, 5};
    int *p = data;

    seek(p, 3, 5);
    std::cout << *p << std::endl;

    return 0;
}
```

The pointer variable `p` in `seek()` is a copy. Any changes to `p` only affect this local copy. The original pointer `p` in `main()` remains unchanged.

32-bit words

Address	Value	Variable
…		
0x91340A08		
0x91340A0C		
0x91340A10		
0x91340A14		
0x91340A18		
0x91340A1C		
0x91340A20		
0x91340A24		
0x91340A28		
0x91340A2C		
0x91340A30		
0x91340A34		
…		

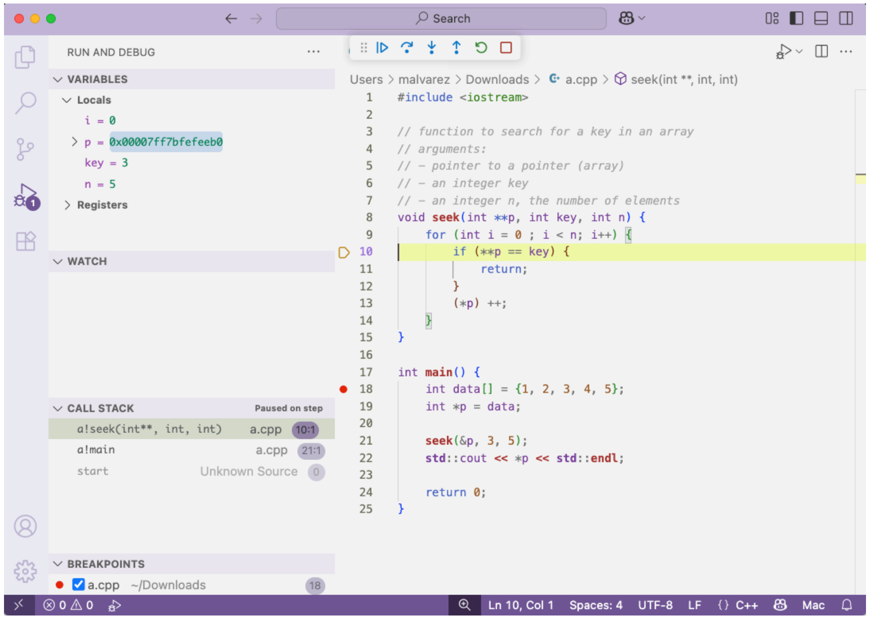
Example: changing a pointer within a function

```
// arguments:
// - pointer to a pointer (array)
// - an integer key
// - an integer n, the number of elements
void seek(int **p, int key, int n) {
    for (int i = 0 ; i < n; i++) {
        if (**p == key) {
            return;
        }
        (*p) ++;
    }
}

int main() {
    int data[] = {1, 2, 3, 4, 5};
    int *p = data;

    seek(&p, 3, 5);
    std::cout << *p << std::endl;

    return 0;
}
```

Solution: to modify the original pointer, can pass a pointer to pointer.

32-bit words

Address	Value	Variable
…		
0x91340A08		
0x91340A0C		
0x91340A10		
0x91340A14		
0x91340A18		
0x91340A1C		
0x91340A20		
0x91340A24		
0x91340A28		
0x91340A2C		
0x91340A30		
0x91340A34		
…		



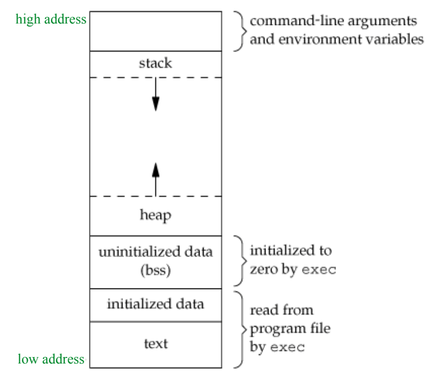
C/C++ memory layout

Memory layout

- What is the C/C++ memory model?
  - a formal specification that defines how programs interact with memory (rules for memory operations — ordering, visibility, synchronization)
    - implementation details are handled by the compiler and CPU architecture
- Memory layout
  - memory is organized into multiple segments (where data is stored)
  - each segment serves a specific purpose and has different properties

Memory layout (segments)

- Text Segment (code)
  - contains **instructions** generated by the compiler
  - marked as read-only
- Data (global/static variables)
  - contains multiple subsections (e.g. initialized data, uninitialized data, constant data)
  - size determined at compilation, addresses resolved during linking
- Heap
  - grows upward (low to high addresses)
  - dedicated to dynamic memory allocation
  - requires explicit management by the programmer
- Stack (local variables, function parameters)
  - grows downward (high to low addresses)
  - no explicit deallocation required



```
#include <iostream>

// global variable
float pi = 3.1416;
// constant global variable
const int min = 100;
// uninitialized global variable
int sum;

void foo(int arg) {
    // local variable
    int i = 1;
    std::cout << "address of arg\t" << &arg << std::endl;
    std::cout << "address of i\t" << &i << std::endl;
}

int main() {
    // heap variable
    int *A = new int[10];

    std::cout << "address of pi\t" << &pi << std::endl;
    std::cout << "address of min\t" << &min << std::endl;
    std::cout << "address of sum\t" << &sum << std::endl;
    std::cout << "value of A\t" << A << std::endl;
    std::cout << "address of A\t" << &A << std::endl;
    std::cout << "address of main\t" << (void*) &main << std::endl;
    std::cout << "address of foo\t" << (void*) &foo << std::endl;
    foo(5);

    delete [] A;

    return 0;
}
```

```
./prog | sort -k 4
```

```
address of foo  0x0000000105499fc0
address of main 0x000000010549a0f0
address of min  0x000000010549af48
address of pi   0x000000010549c000
address of sum  0x000000010549c004
value of A      0x00007fd29f705e90
address of i    0x00007ff7baa66438
address of arg  0x00007ff7baa6643c
address of A    0x00007ff7baa66460
```

NOTE: (64-bit addresses)

Can you tell what are the memory locations grouped by different colors?

What happens if you run the program multiple times?

Dynamic memory allocation

- Static vs dynamic memory
  - **static memory** (stack): size known at compile-time
  - **dynamic memory** (heap): size determined at runtime
- Why dynamic memory?
  - useful for variable-sized data (e.g., user input, large arrays)
  - complex data structures (linked lists, trees, graphs)

Programmer responsibility to pair every new with corresponding delete

- C++ operators

new	delete
• allocates memory on the heap at runtime • returns pointer to the allocated memory location • two forms: single object allocation and array allocation • throws exception if allocation fails	• deallocates memory previously allocated with new • calls destructor for objects before freeing memory • must match allocation type: single delete for single objects, array delete for arrays • does not set pointer to null after deallocation

- Critical rules
  - every `new` must have exactly one matching `delete`
  - deleting the same pointer twice causes undefined behavior
  - accessing deleted memory leads to undefined behavior

Using new/delete

```
int* p = new int;         // allocate single int
int* arr = new int[10];   // allocate array of 10 ints

delete p;                 // free single object
delete [] arr;            // free array
```

```
int *ptr1 = new int[100];
int *ptr2 = ptr1;   // both pointers reference the same address

delete [] ptr1; // array is freed
delete [] ptr2; // ERROR: attempting to delete already freed memory
```


Pointer safety issues

- Null pointers
  - dereferencing a null pointer causes *undefined behavior*
  - example:

```
int *p = nullptr;
*p = 5;
```

- Uninitialized pointers
  - using a pointer before assigning it a valid address results in unpredictable behavior
  - example:

```
int *p;
*p = 10;
```

- Dangling Pointers
  - occur when a pointer refers to memory that has already been freed or gone out of scope
  - example: returning the address of a local variable from a function

Pointer safety issues

- Memory Leaks
  - ✓ dynamically allocated memory that is never freed accumulates and wastes memory
  - ✓ in long-running systems, this can exhaust available memory
- Buffer overflow
  - ✓ writing past the end of an allocated block corrupts adjacent memory and may lead to crashes or exploitable vulnerabilities
  - ✓ example: indexing out of array bounds with a pointer
- Pointer/Array confusion
  - ✓ arrays decay to pointers, but they are not the same, array names are **constant** addresses
  - ✓ `sizeof(array)` => total size in bytes of all elements
  - ✓ `sizeof(pointer)` => size of the pointer variable itself (e.g., 8 bytes on a 64-bit machine)
  - ✓ misunderstanding this leads to incorrect memory usage and errors

Best practices

- Initialization
  - ✓ always initialize pointers, use `nullptr` instead of `0` or `NULL`
- Prefer smart pointers
  - ✓ (`std::unique_ptr, std::shared_ptr, std::weak_ptr`) instead of raw pointers for dynamic memory — not covered in class
  - ✓ they automatically manage lifetime and prevent leaks/dangling references
- Avoid manual memory management
  - ✓ use containers (`std::vector, std::string, std::array`) instead of raw arrays

Important C++ topics to review

- Memory model and pointers
- Dynamic memory allocation
- Classes and objects
- References
- Templates
- STL containers