CSC 212: Data Structures and Abstractions

02: C++ Review, Memory, and Pointers

Prof. Marco Alvarez

Department of Computer Science and Statistics
University of Rhode Island

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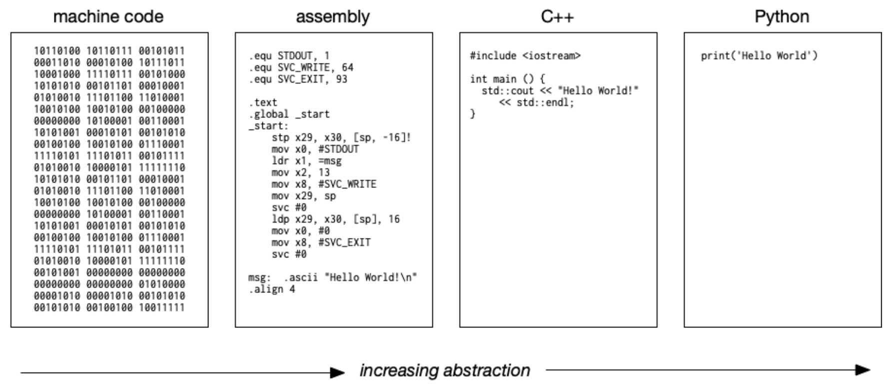
Context



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

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:

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

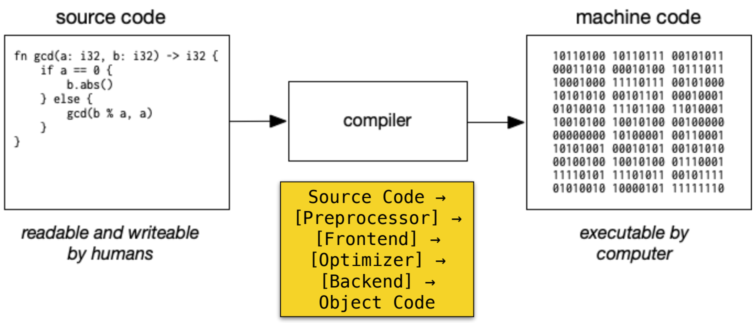
Version	Implementation	Running time (s)	GFLOPS	Absolute speedup	Relative speedup	Fraction of peak (%)
1	Python	25,552.48	0.005	1	—	0.00
2	Java	2,372.68	0.058	11	10.8	0.01
3	C	542.67	0.253	47	4.4	0.03
4	Parallel loops	69.80	1.969	366	7.8	0.24
5	Parallel divide and conquer	3.80	36.180	6,727	18.4	4.33
6	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

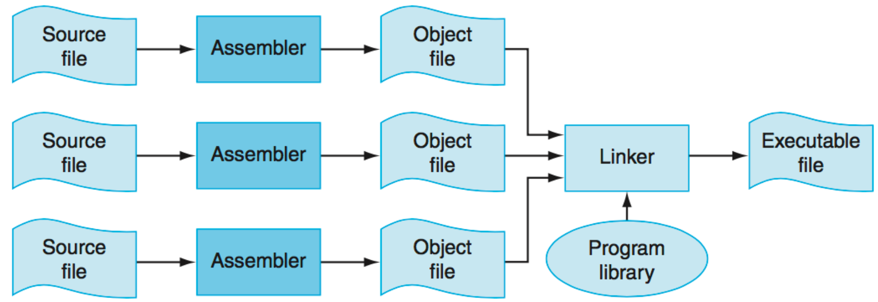
- Compilation
  - ✓ high level source **translated** into another language
    - often into a machine-specific instructions
    - translation occurs through multiple phases
  - ✓ compilers can perform **optimizations** to make the code more efficient, resulting in faster execution (higher performance)
  - ✓ 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



Compiling/linking/running C programs



What is the output?

```cpp
#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;
}
```


Range of values (fundamental types)

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

Integral 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`						

Memory organization

Memory organization

- Memory as a byte array
  - ✓ used to store **data and instructions** for computer programs
  - ✓ contiguous sequence of bytes
  - ✓ 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

Memory organization

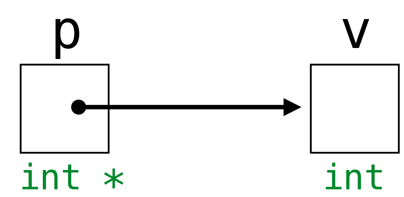
- Data representation in memory
  - ✓ variables stored as byte sequences
  - ✓ interpretation and number of bytes depends on type
    - integers, floating-point numbers, characters, etc.
- OS provides private address space to each **"process"**
  - ✓ process: a program being executed
  - ✓ address space: enormous arrays of bytes visible to the process
  - ✓ typically implemented through virtual memory

Pointers

Variables and pointers

- Every variable exists at a **memory address**
  - ✓ memory address corresponds to a unique location
  - ✓ regardless of variable scope
- The compiler translates names to addresses when generating machine code

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



Pointers

- Declaration
  - ✓ like other variables, must be declared before use
  - ✓ 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

32-bit words

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

    // ...

    return 0;
}
```

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

Pointer operators

32-bit words

```
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;
}
```

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

Pointers and functions

32-bit words

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

int main() {
    int var = 10;

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

    // ...

    return 0;
}
```

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 memory addresses, but works differently than regular arithmetic
- Key Rules
  - ✓ can add/subtract integer values to pointers (`p + n`)
  - ✓ memory addresses are numbers, typically displayed in hexadecimal format but can be viewed in decimal
  - ✓ adding `n` to a pointer `p` moves it forward by (`n * sizeof(*p)`) bytes
- Warning
  - ✓ adding 1 to a pointer does NOT mean adding 1 byte, must understand the size of the underlying data type
  - ✓ 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
```


Example: changing a pointer within a function

```
#include <stdio.h>

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(data, 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.

Example: changing a pointer within a function

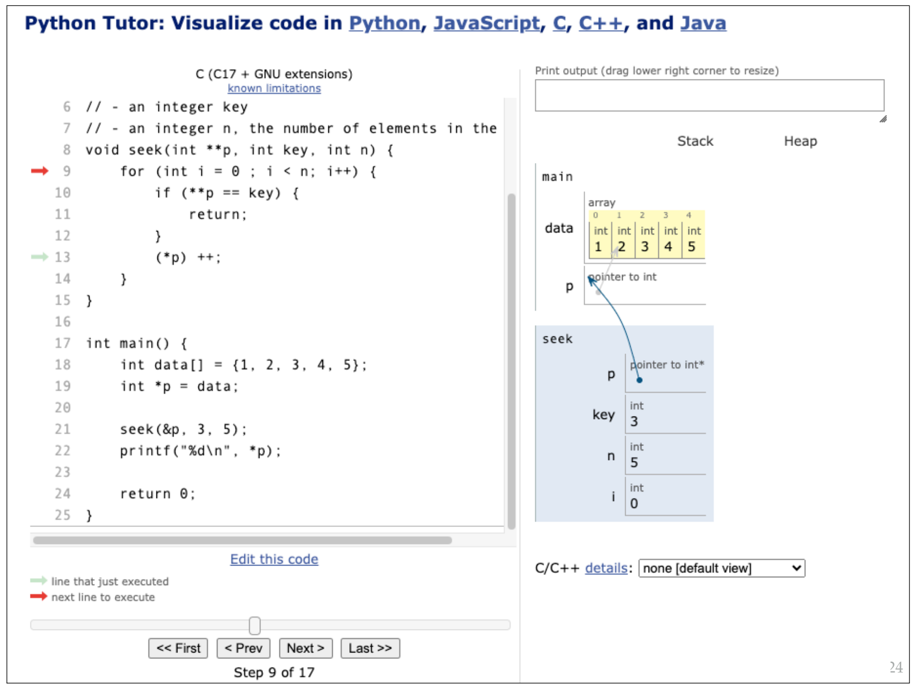
```
// function to search for a key in an array
// arguments:
// - pointer to a pointer (array)
// - an integer key
// - an integer n, the number of elements
void seek(int **p, int key, int n) {
    for (int i = 0 ; i < n; i++) {
        if (**p == key) {
            return;
        }
        (*p) ++;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

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, pass a pointer to the pointer.



Important considerations

- Null pointer initialization
  - ✓ proper initialization of pointers is crucial using the modern `nullptr` keyword, which provides type safety and clarity over older methods like NULL or 0
- Memory leaks
  - ✓ occur when dynamically allocated memory isn't properly freed
- Dangling pointers
  - ✓ occur when they reference memory that has been freed or is no longer valid
- Pointers and arrays
  - ✓ arrays decay to pointers to their first element in most contexts
    - array names provide the address of the first element
    - unlike pointers, array names are constants and cannot be treated as variables
- Safety Guidelines
  - ✓ always initialize pointers before use
  - ✓ track memory allocation and deallocation carefully
  - ✓ validate pointer validity before dereferencing
  - ✓ understand the distinction between arrays and pointers