

# Modern C++ Programming

## 22. PERFORMANCE OPTIMIZATION II

### CODE OPTIMIZATION

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## 1 I/O Operations

- `printf`
- Memory Mapped I/O
- Speed Up Raw Data Loading

## 2 Memory Optimizations

- Heap Memory
- Stack Memory
- Cache Utilization
- Memory Alignment
- Memory Prefetch

## **3** Arithmetic Types

- Data Types
- Arithmetic Operations
- Conversion
- Floating-Point
- Compiler Intrinsic Functions
- Value in a Range
- Lookup Table

## 4 Control Flow

- Branches
- Branch Hints - `[[likely]]` / `[[unlikely]]`
- Signed/Unsigned Integers
- Loops
- Loop Hoisting
- Loop Unrolling
- Assertions
- Compiler Hints - `[[assume]]`/`std::unreachable()`
- Recursion

## **5** Functions

- Function Call Cost
- Argument Passing
- Function Inlining
- Function Attributes
- Pointers Aliasing

## **6** Object-Oriented Programming

## **7** Std Library and Other Language Aspects

# I/O Operations

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**I/O Operations are orders of magnitude slower than  
memory accesses**

In general, input/output operations are one of the most expensive

- Use `endl` for `ostream` only when it is strictly necessary (prefer `\n`)
- Disable *synchronization* with `printf/scanf` :  
`std::ios_base::sync_with_stdio(false)`
- Disable IO *flushing* when mixing `istream/ostream` calls:  
`<istream_obj>.tie(nullptr);`
- Increase IO *buffer size*:  
`file.rdbuf()->pubsetbuf(buffer_var, buffer_size);`



# I/O Streams - Example

```
#include <iostream>

int main() {
    std::ifstream fin;
    // -----
    std::ios_base::sync_with_stdio(false); // sync disable
    fin.tie(nullptr);                      // flush disable
                                          // buffer increase

    const int BUFFER_SIZE = 1024 * 1024; // 1 MB
    char buffer[BUFFER_SIZE];
    fin.rdbuf()->pubsetbuf(buffer, BUFFER_SIZE);
    // -----
    fin.open(filename); // Note: open() after optimizations

    // IO operations
    fin.close();
}
```

- `printf` is faster than `ostream` (see [speed test link](#))
- A `printf` call with a simple format string ending with `\n` is converted to a `puts()` call

```
printf("Hello World\n");  
printf("%s\n", string);
```

- No optimization if the string is not ending with `\n` or one or more `%` are detected in the format string

# Memory Mapped I/O

A **memory-mapped file** is a segment of virtual memory that has been assigned a direct byte-for-byte correlation with some portion of a file

## Benefits:

- Orders of magnitude faster than system calls
- Input can be “cached” in RAM memory (page/file cache)
- A file requires disk access only when a new page boundary is crossed
- Memory-mapping may bypass the page/swap file completely
- Load and store *raw* data (no parsing/conversion)

```
#if !defined(__linux__)
    #error It works only on linux
#endif
#include <fcntl.h>           //::open
#include <sys/mman.h>        //::mmap
#include <sys/stat.h>        //::open
#include <sys/types.h>       //::open
#include <unistd.h>          //::lseek
// usage: ./exec <file> <byte_size> <mode>
int main(int argc, char* argv[]) {
    size_t file_size = std::stoll(argv[2]);
    auto is_read = std::string(argv[3]) == "READ";
    int fd = is_read ? ::open(argv[1], O_RDONLY) :
                ::open(argv[1], O_RDWR | O_CREAT | O_TRUNC, S_IRUSR | S_IWUSR);
    if (fd == -1)
        ERROR("::open")           // try to get the last byte
    if (::lseek(fd, static_cast<off_t>(file_size - 1), SEEK_SET) == -1)
        ERROR("::lseek")
    if (!is_read && ::write(fd, "", 1) != 1) // try to write
        ERROR("::write")
}
```

```
auto mm_mode = (is_read) ? PROT_READ : PROT_WRITE;

// Open Memory Mapped file
auto mmap_ptr = static_cast<char*>(
    ::mmap(nullptr, file_size, mm_mode, MAP_SHARED, fd, 0) );

if (mmap_ptr == MAP_FAILED)
    ERROR("::mmap");
// Advise sequential access
if (::madvise(mmap_ptr, file_size, MADV_SEQUENTIAL) == -1)
    ERROR("::madvise");

// MemoryMapped Operations
// read from/write to "mmap_ptr" as a normal array: mmap_ptr[i]

// Close Memory Mapped file
if (::munmap(mmap_ptr, file_size) == -1)
    ERROR("::munmap");
if (::close(fd) == -1)
    ERROR("::close");
```

Consider using optimized (low-level) numeric conversion routines:

```
template<int N, unsigned MUL, int INDEX = 0>
struct fastStringToIntStr;

inline unsigned fastStringToUnsigned(const char* str, int length) {
    switch(length) {
        case 10: return fastStringToIntStr<10, 1000000000>::aux(str);
        case 9:  return fastStringToIntStr< 9, 100000000>::aux(str);
        case 8:  return fastStringToIntStr< 8, 10000000>::aux(str);
        case 7:  return fastStringToIntStr< 7, 1000000>::aux(str);
        case 6:  return fastStringToIntStr< 6, 100000>::aux(str);
        case 5:  return fastStringToIntStr< 5, 10000>::aux(str);
        case 4:  return fastStringToIntStr< 4, 1000>::aux(str);
        case 3:  return fastStringToIntStr< 3, 100>::aux(str);
        case 2:  return fastStringToIntStr< 2, 10>::aux(str);
        case 1:  return fastStringToIntStr< 1, 1>::aux(str);
        default: return 0;
    }
}
```

```
template<int N, unsigned MUL, int INDEX>
struct fastStringToIntStr {
    static inline unsigned aux(const char* str) {
        return static_cast<unsigned>(str[INDEX] - '0') * MUL +
            fastStringToIntStr<N - 1, MUL / 10, INDEX + 1>::aux(str);
    }
};

template<unsigned MUL, int INDEX>
struct fastStringToIntStr<1, MUL, INDEX> {
    static inline unsigned aux(const char* str) {
        return static_cast<unsigned>(str[INDEX] - '0');
    }
};
```

- Hard disk is orders of magnitude slower than RAM
- Parsing is faster than data reading
- Parsing can be avoided by using *binary* storage and `mmap`
- Decreasing the number of hard disk accesses improves the performance → **compression**

**LZ4** is lossless compression algorithm providing *extremely fast decompression* up to 35% of `memcpy` and good compression ratio  
[github.com/lz4/lz4](https://github.com/lz4/lz4)

Another alternative is **Facebook zstd**  
[github.com/facebook/zstd](https://github.com/facebook/zstd)



Performance comparison of different methods for a file of 4.8 GB of integer values

| Load Method                                       | Exec. Time | Speedup |
|---|------------|---------|
| <code>ifstream</code>                             | 102 667 ms | 1.0x    |
| <code>memory mapped + parsing (first run)</code>  | 30 235 ms  | 3.4x    |
| <code>memory mapped + parsing (second run)</code> | 22 509 ms  | 4.5x    |
| <code>memory mapped + lz4 (first run)</code>      | 3 914 ms   | 26.2x   |
| <code>memory mapped + lz4 (second run)</code>     | 1 261 ms   | 81.4x   |

NOTE: the size of the Lz4 compressed file is 1,8 GB

# Memory Optimizations

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- *Dynamic heap allocation is expensive:* implementation dependent and interact with the operating system
- *Many small heap allocations are more expensive than one large memory allocation*  
The default page size on Linux is 4 KB. For smaller/multiple sizes, C++ uses a sub-allocator
- *Allocations within the page size is faster than larger allocations (sub-allocator)*

# Stack Memory

- *Stack memory is faster than heap memory.* The stack memory provides high locality, it is small (cache fit), and its size is known at compile-time
- `static` stack allocations produce better code. It avoids filling the stack each time the function is reached
- `constexpr` arrays with dynamic indexing produces very inefficient code with GCC. Use `static constexpr` instead

```
void f(int x) {  
    // bad performance with GCC  
    // constexpr      int array[] = {1,2,3,4,5,6,7,8,9};  
    static constexpr int array[] = {1,2,3,4,5,6,7,8,9};  
    return array[x];  
}
```

## Maximize cache utilization:

- Maximize spatial and temporal locality (see next examples)
- Prefer small data types
- Prefer `std::vector<bool>` over array of `bool`
- Prefer `std::bitset<N>` over `std::vector<bool>` if the data size is known in advance or bounded
- Prefer *stack* data structures *instead* of *heap* data structures, e.g. `std::vector` vs. `static_vector` [↗](#)

A, B, C matrices of size  $N \times N$

$$C = A * B$$

```
for (int i = 0; i < N; i++) {  
    for (int j = 0; j < N; j++) {  
        int sum = 0;  
        for (int k = 0; k < N; k++)  
            sum += A[i][k] * B[k][j]; // row x column  
        C[i][j] = sum;  
    }  
}
```

$$C = A * B^T$$

```
for (int i = 0; i < N; i++) {  
    for (int j = 0; j < N; j++) {  
        int sum = 0;  
        for (int k = 0; k < N; k++)  
            sum += A[i][k] * B[j][k]; // row x row  
        C[i][j] = sum;  
    }  
}
```

## Benchmark:

| N                  | 64     | 128  | 256   | 512    | 1024     |
|--------------------|--------|------|-------|--------|----------|
| A * B              | < 1 ms | 5 ms | 29 ms | 141 ms | 1,030 ms |
| A * B <sup>T</sup> | < 1 ms | 2 ms | 6 ms  | 48 ms  | 385 ms   |
| Speedup            | /      | 2.5x | 4.8x  | 2.9x   | 2.7x     |

# Temporal-Locality Example

## Speeding up a random-access function

```
for (int i = 0; i < N; i++) // V1
    out_array[i] = in_array[hash(i)];
```

```
for (int K = 0; K < N; K += CACHE) { // V2
    for (int i = 0; i < N; i++) {
        auto x = hash(i);
        if (x >= K && x < K + CACHE)
            out_array[i] = in_array[x];
    }
}
```

V1 : 436 ms, V2 : 336 ms  $\rightarrow$  1.3x speedup (temporal locality improvement)

.. but it needs a careful evaluation of `CACHE`, and it can even decrease the performance for other sizes

pre-sorted `hash(i)` : 135 ms  $\rightarrow$  3.2x speedup (spatial locality improvement)



# Memory Alignment

**Memory alignment** refers to placing data in memory at addresses that conform to certain boundaries, typically powers of two (e.g., 1, 2, 4, 8, 16 bytes, etc.)

Note: For multidimensional data, alignment only means that the start address of the data is aligned, not that all start offsets for all dimensions are aligned., e.g. for a 2D matrix, if `row[0][0]` is aligned doesn't imply that `row[0][1]` has the same property. Also the strides between rows need to be multiple of the alignment

**Data alignment** is classified in:

- **Internal alignment** for struct/class layout optimization → reducing memory footprint, optimizing memory bandwidth, and minimizing cache-line misses
- **External alignment** across several elements of the same type → minimizing cache-line misses, vectorization (SIMD instructions)

# Internal Structure Alignment

```
struct A1 {  
    char   x1; // offset 0  
    double y1; // offset 8!! (not 1)  
    char   x2; // offset 16  
    double y2; // offset 24  
    char   x3; // offset 32  
    double y3; // offset 40  
    char   x4; // offset 48  
    double y4; // offset 56  
    char   x5; // offset 64 (65 bytes)  
}
```

```
struct A2 { // internal alignment  
    char   x1; // offset 0  
    char   x2; // offset 1  
    char   x3; // offset 2  
    char   x4; // offset 3  
    char   x5; // offset 4  
    double y1; // offset 8  
    double y2; // offset 16  
    double y3; // offset 24  
    double y4; // offset 32 (40 bytes)  
}
```

- (1) We are wasting 40% of memory for ( A1 )
- (2) Considering an *array of structures* (AoS) and a cache line of 64 bytes (x64 processors), every access to A1 involves two cache line operations (~2x slower)

In addition to internal layout problems, even the structure `A2` introduces overhead if organized in an array. Loads lead to one or two cache line operations depending on the alignment at a specific index, e.g.

`index 0` → one cache line load

`index 1` → two cache line loads

It is possible to fix the structure alignment in two ways:

- **Memory padding** refers to manually introducing extra bytes at the end of the data structure to enforce memory alignment.  
e.g. add a `char` array of size 24 to the structure `A2`
- **Align keyword or attribute** allows specifying the alignment requirement of a type or an object (next slide)

- *Explicit* alignment/padding for **variable / struct declaration** → affects `sizeof(T)`

C++11 : `alignas(N)`

GCC/Clang : `__attribute__((aligned(N)))`

MSVC : `__declspec(align(N))`

- *Explicit* alignment for **pointers**

C++20 : `std::assume_aligned<N>(ptr) (<memory>)`

C++17 : `aligned new` or `std::aligned_alloc(align, size)`

GCC/Clang : `__builtin_assume_aligned(ptr, N)`

```
struct alignas(16) S1 { // C++11
    int x, y;
};
struct __attribute__((aligned(16))) S2 { // compiler-specific attribute
    int x, y;
};
constexpr auto MaxAlign = __STDCPP_DEFAULT_NEW_ALIGNMENT__;

S1 s; // 16B alignment
alignas(16) int var[3]; // 16B alignment
auto ptr1 = new S1[10]; // Warning! no alignment guarantee

auto ptr2 = new int[100]; // alignment: max(4B, MaxAlign)
auto ptr3 = std::aligned_alloc(8, 4); // C++17, alignment: max(8B, MaxAlign)
auto ptr4 = __builtin_assume_aligned(ptr2, 16); // compiler-specific attribute
auto ptr5 = std::assume_aligned<16>(ptr2); // C++20

auto ptr = new (std::align_val_t(4)) int[2]; // C++17, max(16B, MaxAlign)
::operator delete[] (ptr, std::align_val_t{4});
```

# Memory Prefetch

`__builtin_prefetch` is used to *minimize cache-miss latency* by moving data into a cache before it is accessed. It can be used not only for improving *spatial locality*, but also *temporal locality*

```
for (int i = 0; i < size; i++) {
    auto data = array[i];
    __builtin_prefetch(array + i + 1, 0, 1); // 2nd argument, '0' means read-only
                                           // 3th argument, '1' means
                                           // temporal locality=1, default=3
    // do some computation on 'data', e.g. CRC
}
```

Alternatively, `-fprefetch-loop-arrays` can be used to emit prefetching instructions

## Multi-Threading and Caches

The **CPU/threads affinity** controls how a process is mapped and executed over multiple cores (including sockets). It affects the process performance due to core-to-core communication and cache line invalidation overhead

Maximizing threads “*clustering*” on a single core can potentially lead to higher cache hits rate and faster communication. On the other hand, if the threads work independently/almost independently, namely they show high locality on their working set, mapping them to different cores can improve the performance

# Arithmetic Types

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# Hardware Notes

- Instruction throughput greatly depends on processor model and characteristics, e.g., there is no hardware support for integer division on GPUs. This operation is translated to 100 instructions for 64-bit operands
- Modern processors provide separated units for floating-point computation (FPU)
- *Addition, subtraction, and bitwise operations* are computed by the ALU, and they have very similar throughput
- In modern processors, *multiplication* and *addition* are computed by the same hardware component for decreasing circuit area → multiplication and addition can be fused in a single operation `fma` (floating-point) and `mad` (integer)

- **32-bit integral vs. floating-point:** in general, integral types are faster, but it depends on the processor characteristics
- **32-bit types are faster than 64-bit types**
  - 64-bit integral types are slightly slower than 32-bit integral types. Modern processors widely support native 64-bit instructions for most operations, otherwise they require multiple operations
  - Single precision floating-points are up to three times faster than double precision floating-points
- **Small integral types are slower than 32-bit integer**, but they require less memory → cache/memory efficiency

- Arithmetic increment/decrement `x++ / x--` has the same performance of `x + 1 / x - 1`
- Arithmetic compound operators (`a *= b`) has the same performance of assignment + operation (`a = a * b`) \*
- **Prefer prefix increment/decrement** (`++var`) instead of the postfix operator (`var++`) \*

---

\* the compiler automatically applies such optimization whenever possible. This is not ensured for object types

- **Keep near constant values/variables** → the compiler can merge their values
- Some operations on **unsigned types** are faster than on **signed types** because they don't have to deal with negative numbers, e.g. `x / 2 → x >> 1`
- Some operations on **signed types** are faster than on **unsigned types** because they can exploit *undefined behavior*, see next slide
- Prefer **logic operations** `||` to **bitwise operations** `|` to take advantage of short-circuiting

```
bool mainGuT(uint32_t i1, uint32_t i2, // if i1, i2 are int32_t, the code
          uint8_t *block) {          // uses half of the instructions!!
    uint8_t c1, c2;
    // 1                               // why? if i1, i2 are uint32_t the compiler
    c1 = block[i1], c2 = block[i2];    // must copy them into 32-bit registers to
    if (c1 != c2) return (c1 > c2);    // ensure wrap-around behavior before passing
    i1++, i2++;                        // them to the subscript operator (size_t)

    // 2                               // On the other hand, int32_t overflow is
    c1 = block[i1], c2 = block[i2];    // undefined behavior and the compiler can
    if (c1 != c2) return (c1 > c2);    // assume it never happens
    i1++, i2++;

    // ... continue repeating the      // the code is also optimal with size_t on 64-bit
} // code multiple times              // arch because block cannot be larger than it
```

# Arithmetic Operations - Integer Multiplication

Integer multiplication requires double the number of bits of the operands

```
// 32-bit platforms

int f1(int x, int y) {
    return x * y;           // efficient but can overflow
}

int64_t f2(int64_t x, int64_t y) {    // same for f2(int x, int64_t y)
    return x * y;           // always correct but slow
}

int64_t f3(int x, int y) {
    return x * static_cast<int64_t>(y); // correct and efficient!!
}
```

## Arithmetic Operations - Power-of-Two Multiplication/Division/Modulo

- Prefer shift for **power-of-two multiplications** ( $a \ll b$ ) and **divisions** ( $a \gg b$ ) only for run-time values \*
- Prefer bitwise AND ( $a \% b \rightarrow a \& (b - 1)$ ) for **power-of-two modulo operations** only for run-time values \*
- **Constant multiplication and division** can be heavily optimized by the compiler, even for non-trivial values

---

\* the compiler automatically applies such optimizations if  $b$  is known at compile-time. Bitwise operations make the code harder to read

Ideal divisors: when a division compiles down to just a multiplication

# Conversion

---

| From           | To              | Cost   |
|----------------|-----------------|--|
| Signed         | Unsigned        | no cost, bit representation is the same  |
| Unsigned       | Larger Unsigned | no cost, register extended   |
| Signed         | Larger Signed   | 1 clock-cycle, register + sign extended  |
| Integer        | Floating-point  | 4-16 clock-cycles<br>Signed → Floating-point is faster than<br>Unsigned → Floating-point (except AVX512<br>instruction set is enabled) |
| Floating-point | Integer         | fast if SSE2, slow otherwise (50-100 clock-cycles)   |

---



# Floating-Point Division

## Multiplication is much faster than division\*

not optimized:

```
// "value" is floating-point (dynamic)  
for (int i = 0; i < N; i++)  
    A[i] = B[i] / value;
```

optimized:

```
div = 1.0 / value;    // div is floating-point  
for (int i = 0; i < N; i++)  
    A[i] = B[i] * div;
```

---

\* Multiplying by the inverse is not the same as the division  
see [lemire.me/blog/2019/03/12](http://lemire.me/blog/2019/03/12)

# Floating-Point FMA

Modern processors allow performing `a * b + c` in a single operation, called **fused multiply-add** (`std::fma` in C++11). This implies better performance and accuracy

CPU processors perform computations with a larger register size than the original data type (e.g. 48-bit for 32-bit floating-point) for performing this operation

Compiler behavior:

- GCC 9 and ICC 19 produce a single instruction for `std::fma` and for `a * b + c` with `-O3 -march=native`
- Clang 9 and MSVC 19.\* produce a single instruction for `std::fma` but not for `a * b + c`

---

FMA: solve quadratic equation

FMA: extended precision addition and multiplication by constant

**Compiler intrinsics** are highly optimized functions directly provided by the compiler instead of external libraries

*Advantages:*

- Directly mapped to hardware functionalities if available
- Inline expansion
- Do not inhibit high-level optimizations, and they are portable contrary to `asm` code

*Drawbacks:*

- Portability is limited to a specific compiler
- Some intrinsics do not work on all platforms
- The same intrinsics can be mapped to a non-optimal instruction sequence depending on the compiler

Most compilers provide intrinsics **bit-manipulation functions** for SSE4.2 or ABM (Advanced Bit Manipulation) instruction sets for Intel and AMD processors

GCC examples:

`__builtin_popcount(x)` count the number of one bits

`__builtin_clz(x)` (count leading zeros) counts the number of zero bits following the most significant one bit

`__builtin_ctz(x)` (count trailing zeros) counts the number of zero bits preceding the least significant one bit

`__builtin_ffs(x)` (find first set) index of the least significant one bit

- Compute integer `log2`

```
inline unsigned log2(unsigned x) {  
    return 31 - __builtin_clz(x);  
}
```

- Check if a number is a power of 2

```
inline bool is_power2(unsigned x) {  
    return __builtin_popcount(x) == 1;  
}
```

- Bit search and clear

```
inline int bit_search_clear(unsigned x) {  
    int pos = __builtin_ffs(x); // range [0, 31]  
    x      &= ~(1u << pos);  
    return pos;  
}
```

## Example of intrinsic portability issue:

`__builtin_popcount()` GCC produces `__popcountdi2` instruction while Intel Compiler (ICC) produces 13 instructions

`_mm_popcnt_u32` GCC and ICC produce `popcnt` instruction, but it is available only for processor with support for SSE4.2 instruction set

## More advanced usage

- Compute CRC: `_mm_crc32_u32`
- AES cryptography: `_mm256_aesenclast_epi128`
- Hash function: `_mm_sha256msg1_epu32`

*Using intrinsic instructions is extremely dangerous if the target processor does not natively support such instructions*

Example:

*“If you run code that uses the intrinsic on hardware that doesn’t support the `lzcnt` instruction, the results are unpredictable” - MSVC*

on the contrary, GNU and clang `__builtin_*` instructions are always well-defined. The instruction is translated to a non-optimal operation sequence in the worst case

The instruction set support should be checked at *run-time* (e.g. with `__cpuid` function on MSVC), or, when available, by using compiler-time macro (e.g. `__AVX__`)

# Automatic Compiler Function Transformation

`std::abs` can be recognized by the compiler and transformed to a hardware instruction

In a similar way, C++20 provides a portable and efficient way to express bit operations

`<bit>`

```
rotate left : std::rotr
rotate right : std::rotr
count leading zero : std::countl_zero
count leading one : std::countl_one
count trailing zero : std::countr_zero
count trailing one : std::countr_one
population count : std::popcount
```



## Value in a Range

Checking if a non-negative value  $x$  is within a range  $[A, B]$  can be optimized if  $B > A$  (useful when the condition is repeated multiple times)

```
if (x >= A && x <= B)

// STEP 1: subtract A
if (x - A >= A - A && x - A <= B - A)
// -->
if (x - A >= 0 && x - A <= B - A) // B - A is precomputed

// STEP 2
// - convert "x - A >= 0" --> (unsigned) (x - A)
// - "B - A" is always positive
if ((unsigned) (x - A) <= (unsigned) (B - A))
```

## Value in a Range Examples

Check if a value is an uppercase letter:

```
uint8_t x = ...
```

```
if (x >= 'A' && x <= 'Z')
```

```
...
```

→

```
uint8_t x = ...
```

```
if (x - 'A' <= 'Z')
```

```
...
```

A more general case:

```
int x = ...
```

```
if (x >= -10 && x <= 30)
```

```
...
```

→

```
int x = ...
```

```
if ((unsigned) (x + 10) <= 40)
```

```
...
```

---

The compiler applies this optimization only in some cases  
(tested with GCC/Clang 9 -O3)

# Lookup Table

**Lookup table (LUT)** is a *memoization* technique which allows replacing *runtime* computation with precomputed values

Example: a function that computes the logarithm base 10 of a number in the range [1-100]

```
template<int SIZE, typename Lambda>
constexpr std::array<float, SIZE> build(Lambda lambda) {
    std::array<float, SIZE> array{};
    for (int i = 0; i < SIZE; i++)
        array[i] = lambda(i);
    return array;
}

float log10(int value) {
    constexpr auto lambda = [](int i) { return std::log10f((float) i); };
    static constexpr auto table = build<100>(lambda);
    return table[value];
}
```

Collection of low-level implementations/optimization of common operations:

- **Bit Twiddling Hacks**

`graphics.stanford.edu/~seander/bithacks.html`

- **The Aggregate Magic Algorithms**

`aggregate.org/MAGIC`

- **Hackers Delight Book**

`www.hackersdelight.org`

The same instruction/operation may take different clock-cycles on different architectures/CPU type

- **Agner Fog - Instruction tables** (latencies, throughputs)  
`www.agner.org/optimize/instruction_tables.pdf`
- **Latency, Throughput, and Port Usage Information**  
`uops.info/table.html`

# Control Flow

---

**Computation is faster than decision**

**Pipelines** are an essential element in modern processors. Some processors have up to 20 pipeline stages (14/16 typically)

The downside to long pipelines includes the danger of **pipeline stalls** that waste CPU time, and the time it takes to reload the pipeline on **conditional branch** operations ( `if` , `while` , `for` )



- Prefer `switch` statements to multiple `if`
  - If the compiler does not use a jump-table, the cases are evaluated in order of appearance → the most frequent cases should be placed before
  - Some compilers (e.g. `clang`) are able to translate a sequence of `if` into a `switch`
- In general, a *branch* has negligible effect on performance if it is not taken
- Not all control flow instructions (or branches) are translated into `jump` instructions. If the code in the branch is small, the compiler could optimize it in a conditional instruction, e.g. `ccmovl`  
Small code section can be optimized in different ways <sup>2</sup> (see next slides)

---

Branch predictor: How many 'if's are too many?

<sup>2</sup> Is this a branch?

## Minimize Branch Overhead

- **Branch prediction:** technique to guess which way a branch takes. It requires hardware support, and it is generically based on dynamic history of code executing
- **Branch predication:** a conditional branch is substituted by a sequence of instructions from both paths of the branch. Only the instructions associated to a *predicate* (boolean value), that represents the direction of the branch, are actually executed

```
int x = (condition) ? A[i] : B[i];  
P = (condition) // P: predicate  
@P x = A[i];  
@!P x = B[i];
```

- **Speculative execution:** execute both sides of the conditional branch to better utilize the computer resources and commit the results associated to the branch taken

## Branch Hints - `[[likely]]` / `[[unlikely]]`

C++20 `[[likely]]` and `[[unlikely]]` provide a hint to the compiler to optimize a conditional statement, such as `while`, `for`, `if`

```
for (i = 0; i < 300; i++) {  
    [[unlikely]] if (rand() < 10)  
        return false;  
}
```

```
switch (value) {  
    [[likely]] case 'A': return 2;  
    [[unlikely]] case 'B': return 4;  
}
```

## Signed/Unsigned Integers

- Prefer **signed integer** for **loop indexing**. The compiler optimizes more aggressively such loops because integer overflow is not defined. Unsigned loop indexing generates complex intermediate expressions, especially for nested loops, that the compiler could not solve
- Prefer **32-bit signed integer** or **64-bit integer** for **any operation that is translated to 64-bit**. The most common is *array indexing*. The subscript operator implicitly defines its parameter as `size_t`. Any indexing operation with 32-bit unsigned integer requires the compiler to enforce wrap-around behavior, e.g. by moving the variable to a 32-bit register

```
unsigned v = ...;  
// some operations on v  
array[v];
```

# Loops

- Prefer **square brackets** syntax `[]` over pointer arithmetic operations for array access to facilitate compiler loop optimizations (e.g. polyhedral loop transformations)
- *Range-based* loop could provide minor performance improvements for small loops that iterate over a container <sup>1</sup>
- On the other hand, *range-based loops* and *iterators* could inhibit many optimizations such as loop unrolling and vectorization

---

<sup>1</sup> The Little Things: Everyday efficiencies

# Loop Hoisting

**Loop Hoisting**, also called *loop-invariant code motion*, consists of moving statements or expressions outside the body of a loop *without affecting the semantics* of the program

Base case:

```
for (int i = 0; i < 100; i++)  
    a[i] = x + y;
```

Better:

```
v = x + y;  
for (int i = 0; i < 100; i++)  
    a[i] = v;
```

Loop hoisting is also important in the evaluation of loop conditions

Base case:

```
// "x" never changes  
for (int i = 0; i < f(x); i++)  
    a[i] = y;
```

Better:

```
int limit = f(x);  
for (int i = 0; i < limit; i++)  
    a[i] = y;
```

In the worst case, `f(x)` is evaluated at every iteration (especially when it belongs to another translation unit)

**Loop unrolling** (or **unwinding**) is a loop transformation technique which optimizes the code by removing (or reducing) loop iterations

The optimization produces better code at the expense of binary size

Example:

```
for (int i = 0; i < N; i++)  
    sum += A[i];
```

can be rewritten as:

```
for (int i = 0; i < N; i += 8) {  
    sum += A[i];  
    sum += A[i + 1];  
    sum += A[i + 2];  
    sum += A[i + 3];  
    ...  
} // we suppose N is a multiple of 8
```

## Loop unrolling can make your code better/faster:

- + Improve instruction-level parallelism (ILP)
- + Allow vector (SIMD) instructions
- + Reduce control instructions and branches

## Loop unrolling can make your code worse/slower:

- Increase compile-time/binary size
- Require more instruction decoding
- Use more memory and instruction cache

**Unroll directive** The Intel, IBM, Arm, Nvidia, clang, and GCC compilers provide the preprocessing directive `#pragma unroll` (`#pragma GCC unroll` for GCC) to insert above the loop to force loop unrolling. The compiler already applies the optimization in most cases



# Assertions

Some compilers (e.g. clang) use assertions for optimization purposes: most likely code path, not possible values, etc. <sup>3</sup>



Mehdi Amini  
@JokerEph

And 1h gone easily tracking why an assert build of a microbenchmark was 2x faster (!) than the release build...  
Not CPU scaling this time, not CPU assignment, it was -D\_GLIBCXX\_ASSERTIONS!  
Turns out that LLVM optimizer likes the added assertions and take advantage of these... 🤔

[Traduci post](#)

```
#include "benchmark/benchmark.h"

static void strCpy(benchmark::State& state) {
    std::string x = "hello";
    for (auto _ : state) {
        std::string copy(x);
        copy += " world";
    }
}

BENCHMARK(func: strCpy);
BENCHMARK_MAIN();
```



Mehdi Amini @JokerEph · 16 mar

Seems to me that a bunch of `__builtin_unreachable` and `__builtin_expect` that are part of `_GLIBCXX_ASSERTIONS` should be present in release mode.

Actually, they probably should be there **"only"** in release mode: these aren't assertions, but optimizers hints...



🇷🇺 Andrei Alexandrescu 🇷🇺 @incomputable · 6 apr 2020

Alrighty, so this makes my code 8% faster with g++. I am not kidding:

```
#ifdef NDEBUG
#undef assert
#define assert(c) if (c) {} else { __builtin_unreachable(); }
#endif
```

Why don't they define it like that to start with?

## Compiler Hints - `[[assume]]/std::unreachable()`

C++23 allows defining an *assumption* in the code that is always true

```
int x = ...;
[[assume(x > 0)]]; // the compiler assume that 'x' is positive

int y = x / 2;    // the operation is translated in a single shift as for
                 // the unsigned case
```

C++23 also provides `std::unreachable()` (`<utility>`) for marking unreachable code

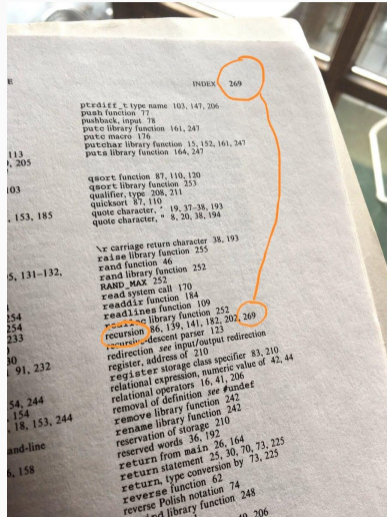
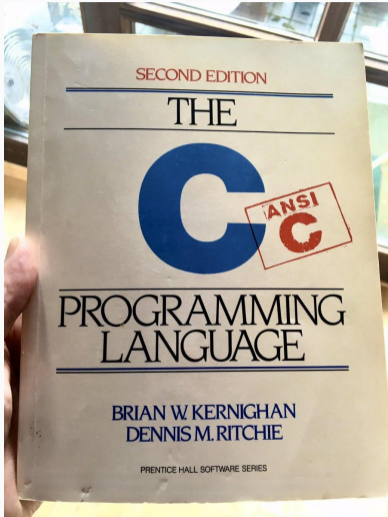
Compilers provide non-portable instructions for previous C++ standards: `__builtin_assume()` (clang), `__builtin_unreachable()` (gcc), `__assume()` (msvc)

Note: sometimes user-provided information leads to worse optimization, see [@llvm.assume blocks optimization](#) and [Refined Input, Degraded Output: The Counterintuitive World of Compiler Behavior](#)

**Avoid run-time recursion** (very expensive). Prefer *iterative* algorithms instead

**Recursion cost:** The program must store all variables (snapshot) at each recursion iteration on the stack, and remove them when the control return to the caller instance

The **tail recursion** optimization avoids maintaining caller stack and pass the control to the next iteration. The optimization is possible only if all computation can be executed before the recursive call



# Functions

---

# Function Call Cost

## Function call methods:

**Direct** Function address is known at compile-time

**Indirect** Function address is known only at run-time

**Inline** The function code is fused in the caller code (same translation unit or Link-time-optimization)

## Direct/Indirect function call cost:

- The caller pushes the arguments on the stack in reverse order
- Jump to function address
- The caller clears (pop) the stack
- The function pushes the return value on the stack
- Jump to the caller address

The **optimal way** to pass and return arguments (*by-value*) to/from functions is in *registers*. It also avoid the pointer aliasing performance issue. The following conditions must be satisfied:

- The object is **trivially copyable**: No user-provided copy/move/default constructors, destructor, and copy/move assignment operators, no virtual functions, apply recursively to base classes and non-static data members
- Linux/Unix (SystemV x86-64 ABI): data types  $\leq$  **16 bytes** ( $8B \times 2$ ), max **6 arguments**
- Windows (x64 ABI): data types  $\leq$  **8 bytes**, max **4 arguments**

- 
- when are structs/classes passed and returned in registers?
  - System V ABI - X86-64 Calling Convention
  - x64 calling convention - Parameter Passing

- If the previous conditions are not satisfied, the object is passed **by-reference**. In addition, objects that are not *trivially-copyable* could be expensive to pass *by-value* (copied).
- Pass **by-reference** and **by-pointer** introduce one level of indirection
- Pass **by-reference** is more efficient than pass **by-pointer** because it facilitates variable elimination by the compiler, and the function code does not require checking for `NULL` pointer



`const` modifier applied to values, pointers, references *does not produce better code* in most cases, but it is useful for ensuring read-only accesses

In some cases, pass `by-const` is beneficial for performance because `const` member function overloading could be cheaper than their counterparts

## inline

`inline` specifier for optimization purposes is just a hint for the compiler that increases the heuristic threshold for **inlining**, namely copying the function body where it is called

```
inline void f() { ... }
```

- the compiler can ignore the hint
- *inlined* functions increase the binary size because they are expanded in-place for every function call

## Compilers have different heuristics for function inlining

- Number of lines (even comments: How new-lines affect the Linux kernel performance)
- Number of assembly instructions
- Inlining depth (recursive)

GCC/Clang extensions allow to *force* inline/non-inline functions:

```
[[gnu::always_inline]] void f() { ... }  
[[gnu::noinline]]      void f() { ... }  
[[msvc::forceinline]] void f() { ... }
```

- 
- An Inline Function is As Fast As a Macro
  - Inlining Decisions in Visual Studio

The compiler can *inline* a function only if it is independent from external references

- A function with *internal linkage* is not visible outside the current translation unit, so it can be aggressively *inlined*
- On the other hand, *external linkage* doesn't prevent function inlining if the function body is visible in a translation unit. In this situation, the compiler can duplicate the function code if it determines that there are no external references

# Symbol Visibility

All compilers, except MSVC, export all function symbols → the symbols can be used in other translation units and this can prevent inlining

Alternatives:

- Use `static` functions
- Use `anonymous namespace` (functions and classes)
- Use GNU extension (also clang) `__attribute__((visibility("hidden")))`

## Function Attributes

Some compilers, including Clang, GCC, provide additional attributes to optimize function calls:

- `__attribute__((pure))` / `[[gnu::pure]]` *no side effects* on its parameters and no external global references (program state)  
→ subject to data flow analysis and might be eliminated
- `__attribute__((const))` / `[[gnu::const]]` *depends only* on its parameters, no read from global references  
→ subject to common sub-expression elimination and loop optimizations

*note:* the compiler is able to deduce such properties in most cases

---

Implications of pure and constant functions

`__attribute__((pure))` function attribute

Consider the following example:

```
// suppose f() is not inline
void f(int* input, int size, int* output) {
    for (int i = 0; i < size; i++)
        output[i] = input[i];
}
```

- The compiler cannot *unroll* the loop (sequential execution, no ILP) because `output` and `input` pointers can be **aliased**, e.g. `output = input + 1`
- The aliasing problem is even worse for more complex code and *inhibits all kinds of optimization* including code re-ordering, vectorization, common sub-expression elimination, etc.

Most compilers (included GCC/Clang/MSVC) provide **restricted pointers** (`__restrict`) so that the programmer asserts that the pointers are not aliased

```
void f(int* __restrict input,
      int      size,
      int* __restrict output) {
    for (int i = 0; i < size; i++)
        output[i] = input[i];
}
```

Potential benefits:

- Instruction-level parallelism
- Less instructions executed
- Merge common sub-expressions



## Benchmarking matrix multiplication

```
void matrix_mul_v1(const int* A,  
                  const int* B,  
                  int      N,  
                  int*     C) {
```

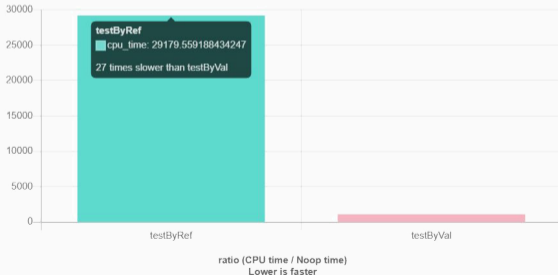
```
void matrix_mul_v2(const int* __restrict A,  
                  const int* __restrict B,  
                  int      N,  
                  int*     __restrict C) {
```

| Optimization | -O1      | -O2    | -O3    |
|--------------|----------|--------|--------|
| v1           | 1,030 ms | 777 ms | 777 ms |
| v2           | 513 ms   | 510 ms | 761 ms |
| Speedup      | 2.0x     | 1.5x   | 1.02x  |

```
void foo(std::vector<double>& v, const double& coeff) {  
    for (auto& item : v) item *= std::sinh(coeff);  
}
```

vs.

```
void foo(std::vector<double>& v, double coeff) {  
    for (auto& item : v) item *= std::sinh(coeff);  
}
```



# Object-Oriented Programming

---

# Variable/Object Scope

## Declare local variable in the innermost scope

- the compiler can more likely fit them into registers instead of stack
- it improves readability

### Wrong:

```
int i, x;
for (i = 0; i < N; i++) {
    x    = value * 5;
    sum += x;
}
```

### Correct:

```
for (int i = 0; i < N; i++) {
    int x    = value * 5;
    sum    += x;
}
```

- C++17 allows local variable initialization in `if` and `while` statements, while C++20 introduces them for in *range-based loops*

## Variable/Object Scope

**Exception!** Built-in type variables and passive structures should be placed in the innermost loop, while objects with constructors should be placed outside loops

```
for (int i = 0; i < N; i++) {  
    std::string str("prefix_");  
    std::cout << str + value[i];  
} // str call CTOR/DTOR N times
```

```
std::string str("prefix_");  
for (int i = 0; i < N; i++) {  
    std::cout << str + value[i];  
}
```

# Object Optimizations

- Prefer **direct initialization** and *full object constructor* instead of two-step initialization (also for variables)
- Prefer **move semantic** instead of *copy constructor*. Mark *copy constructor* as `=delete` (sometimes it is hard to see, e.g. implicit)
- Use `static` for all members that do not use instance member (avoid passing `this` pointer)
- If the object semantic is *trivially copyable*, ensure **defaulted** `= default` *default/copy constructors* and *assignment operators* to enable vectorization

# Object Dynamic Behavior Optimizations

- **Virtual calls** are slower than standard functions
  - Virtual calls prevent any kind of optimizations as function lookup is at runtime (loop transformation, vectorization, etc.)
  - Virtual call overhead is up to 20%-50% for function that can be inlined
- Mark `final` all `virtual` functions that are not overridden
- Avoid dynamic operations, e.g. `dynamic_cast`

- 
- The Hidden Performance Price of Virtual Functions
  - Investigating the Performance Overhead of C++ Exceptions

# Object Operation Optimizations

- Minimize multiple `+` operations between objects to avoid temporary storage
- Prefer `x += obj`, instead of `x = x + obj` → avoid object copy and temporary storage
- Prefer `++obj` / `--obj` (return `&obj`), instead of `obj++`, `obj--` (copy and return old `obj`)



# Object Implicit Conversion

```
struct A { // big object
    int array[10000];
};
struct B {
    int array[10000];

    B() = default;

    B(const A& a) { // user-defined constructor
        std::copy(a.array, a.array + 10000, array);
    }
};
//-----
void f(const B& b) {}

A a;
B b;
f(b); // no cost
f(a); // very costly!! implicit conversion
```

# Std Library and Other Language Aspects

---

- Avoid old C library routines such as `qsort`, `bsearch`, etc. Prefer `std::sort`, `std::binary_search` instead
  - `std::sort` is based on a hybrid sorting algorithm. Quick-sort / head-sort (introsort), merge-sort / insertion, etc. depending on the std implementation
  - Prefer `std::find()` for small array, `std::lower_bound`, `std::upper_bound`, `std::binary_search` for large sorted array

# Function Optimizations

- `std::fill` applies `memset` and `std::copy` applies `memcpy` if the input/output are continuous in memory
- Use the same type for initialization in functions like `std::accumulate()`, `std::fill`

```
auto array = new int[size];  
...  
auto sum = std::accumulate(array, array + size, 0u);  
// 0u != 0 → conversion at each step  
  
std::fill(array, array + size, 0u);  
// it is not translated into memset
```

# Containers

- Use `std` container member functions (e.g. `obj.find()`) instead of external ones (e.g. `std::find()`). Example: `std::set`  $O(\log(n))$  vs.  $O(n)$
- Be aware of container properties, e.g. `vector.push_back(v)`, instead of `vector.insert(vector.begin(), value)` → entire copy of all vector elements
- Set `std::vector` size during the object construction (or use the `reserve()` method) if the number of elements to insert is known in advance → every implicit resize is equivalent to a copy of all vector elements
- Consider *unordered* containers instead of the standard one, e.g. `unordered_map` vs. `map`
- Prefer `std::array` instead of dynamic heap allocation

## Critics to Standard Template Library (STL)

- Platform/Compiler-dependent implementation
- Execution order and results across platforms
- Debugging is hard
- Complex interaction with custom memory allocators
- Error handling based on exceptions is non-transparent
- Binary bloat
- Compile time (see C++ Compile Health Watchdog, and STL Explorer)

## Other Language Aspects

- Prefer `lambda` expression (or `function object`) instead of `std::function` or function pointers
- Avoid dynamic operations: **exceptions** (and use `noexcept`), **smart pointer** (e.g. `std::unique_ptr`)
- Use `noexcept` decorator → program is aborted if an error occurred instead of raising an exception. see  
Bitcoin: 9% less memory: `make SaltedOutpointHasher noexcept`