Modern C++ Programming

23. Performance Optimization II

Code Optimization

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I/O Operations

I/O Operations

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

I/O Streams

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

```cpp
#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`

- `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

---

`www.ciselant.de/projects/gcc_printf/gcc_printf.html`

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)

Memory Mapped I/O - Example

```
#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")
```

Memory Mapped I/O Example

```
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");
```

Low-Level Parsing 1/2

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;
    }
}
```

Low-Level Parsing 2/2

```
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');
    }
};
```

Faster parsing: `lemire.me/blog/tag/simd-swar-parsing`

Speed Up Raw Data Loading 1/2

- 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`

Another alternative is **Facebook zstd**
`github.com/facebook/zstd`

Speed Up Raw Data Loading

Performance comparison of different methods for a file of 4.8 GB of integers. They are explicit values in a text file in the case of `ifstream` and `memory mapped`, while binary values for LZ4

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

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

Memory Optimizations

Heap Memory

- *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];
}
```

Cache Utilization

Maximize cache utilization:

- Maximize spatial and temporal locality (see next examples)
- Prefer small data types
- For basic set query and insertion:
  - Prefer `std::vector<bool>` over a *dynamic* array of `bool`
  - Prefer `std::bitset` over `std::vector<bool>` if the data size is known in advance or bounded. *Fixed-size* array of `bool` should be always replaced by `std::bitset`
  - Remember that common std algorithms could not be optimized for these containers, e.g. `std::count_if`, `std::find`
- Prefer *stack* data structures *instead* of heap data structures, e.g. `std::vector` vs. `static_vector` ↗

Spatial Locality Example

`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 × 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 × row
        C[i][j] = sum;
    }
}
```

Spatial Locality Example

Benchmark:

`N`	64	128	256	512	1024
`A * B`	< 1 ms	5 ms	29 ms	141 ms	1,030 ms
`A * B`^{T}	< 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 → 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 → 3.2x speedup (spatial locality improvement)

`lemire.me/blog/2019/04/27`

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[1][0]` 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**)

---

see also `#pragma pack(1)`

External Structure Alignment 1/3

In addiction 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)

External Structure Alignment

- *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)`

External Structure Alignment 3/3

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

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

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

auto ptr = new (sizeof(int), std::align_val_t{8}); // C++17, max(8B, DefaultAlilgn)
::operator delete (ptr, std::align_val_t{8});
```

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

---

The pros and cons of explicit software prefetching

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

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)

`uops.info: Latency, Throughput, and Port Usage Information`

Data Types

- **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 Operations

- 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

Arithmetic Operations

- **Keep near constant values/variables** → the compiler can merge their values. Floating-point values requires more attention due to non-associativity
- 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

Arithmetic Operations 3/3

```
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
```

Garbage In, Garbage Out: Arguing about Undefined Behavior with Nasal Daemons, Chandler Carruth, CppCon 2016

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, everything is 32-bit
}                                        // can overflow

int64_t f2(int64_t x, int64_t y) {       // not efficient, the compiler emulated
    return x * y;                        // 64-bit operations with 32-bit
}                                        // instructions
                                         // same for f2(int x, int64_t y)
int64_t f3(int x, int y) {
    return x * static_cast<int64_t>(y); // efficient!! the compiler knows that
}                                        // the inputs are 32-bit and the
                                         // multiplication requires 64-bit,
                                         // so not emulation is needed
```

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

- Prefer shift for **power-of-two multiplications** (`a ≪ b`) and **divisions** (`a ≫ b`) only for run-time values *

- Prefer bitwise AND (`a % b → 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 Signed → Floating-point is faster than Unsigned → Floating-point (except `AVX512` instruction set is enabled)
`Floating-point`	`Integer`	fast if `SSE2`, slow otherwise (50-100 clock-cycles)

`Optimizing software in C++`, *Agner Fog*

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`

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 Intrinsic Functions

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 instricics can be mapped to a non-optimal instruction sequence depending on the compiler

Compiler Intrinsic Functions 2/5

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

`gcc.gnu.org/onlinedocs/gcc/Other-Builtins.html`

Compiler Intrinsic Functions

- 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;
}
```

Compiler Intrinsic Functions 4/5

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`

`software.intel.com/sites/landingpage/IntrinsicsGuide/`

Compiler Intrinsic Functions

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::rotl`
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]

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

Low-Level Optimizations

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`

Low-Level Information

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

Control Flow

Computation is faster than decision

Branches 1/2

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`)

Branches 2/2

- 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 [2] (see next slides)

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

[2] 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 [1]
- On the other hand, *range-based loops* and *iterators* could inhibit many optimizations such as loop unrolling and vectorization

---

[1] `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 1/2

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

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

---

`Why are unrolled loops faster?`

Assertions

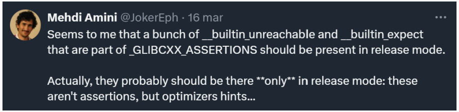
Some compilers (e.g. `clang`) use assertions for optimization purposes: most likely code path, not possible values, etc. [3]

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

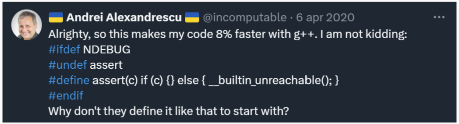
```
#include "benchmark/benchmark.h"

static void strCpy(benchmark::State& state) {
  std::string x = "hello";
  for (auto _: Value : 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`

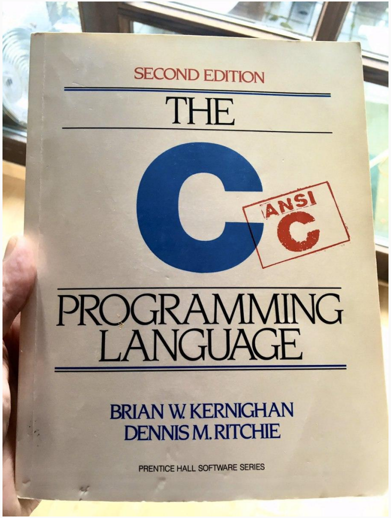
Recursion 1/2

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

Recursion 2/2



SECOND EDITION
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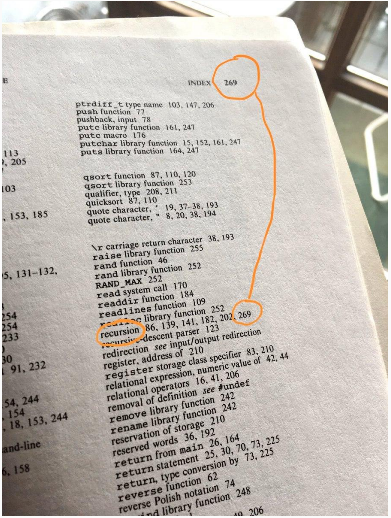

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Via Twitter - Jan Wildeboer

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

Argument Passing

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`

Argument Passing - Active Objects

- 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

---

`Three reasons to pass std::string_view by value`

Argument Passing - `const` Parameters

`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

---

`GoTW#81: Constant Optimization?`

`inline` Function Declaration 1/2

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

`inline` Function Declaration 2/2

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`

Inlining and Linkage

The compiler can *inline* a function only if it is <u>independent</u> 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")))`

`gcc.gnu.org/wiki/Visibility`

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

Pointers Aliasing 1/4

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.

Pointers Aliasing

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

Pointers Aliasing

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) {
```

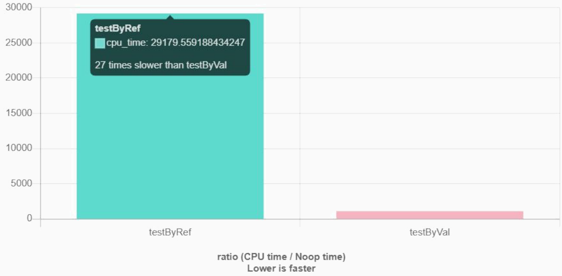
Optimization	`-O1`	`-O2`	`-O3`
v1	1,030 ms	777 ms	777 ms
v2	513 ms	510 ms	761 ms
Speedup	2.0x	1.5x	1.02x

Pointers Aliasing

```
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 `switch` 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

From C to C++

- 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`)

`STL isn't for *anyone*`

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`