Modern C++ Programming

17. Performance Optimization II

Code Optimization

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Table of Context

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

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


```cpp
#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

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

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

Speed Up Raw Data Loading

- 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 integer values

Load Method	Exec. Time	Speedup
`ifstream`	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
- 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

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

Data Alignment

Data alignment allows avoiding unnecessary memory accesses, and it is also essential to exploit hardware vector instructions (SIMD) like `SSE`, `AVX`, etc.

- **Internal alignment**: reducing memory footprint, optimizing memory bandwidth, and minimizing cache-line misses
- **External alignment**: minimizing cache-line misses

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)
}
```

Considering an *array of structures* (*AoS*), there are two problems:

- We are wasting 40% of memory in the first case (`A1`)
- In common x64 processors the cache line is 64 bytes. For the first structure `A1` , every access involves two cache line operations (2x slower)

see also `#pragma pack(1)`

External Structure Alignment and Padding

Considering the previous example for the structure `A2`, random loads from an array of structures `A2` leads 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:

- The **memory padding** refers to introduce extra bytes at the end of the data structure to enforce the 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 in C++

C++ allows specifying the alignment requirement in different ways:

- C++11 `alignas(N)` only for variable / struct declaration
- C++17 aligned `new` (e.g. `new int[2, N]`)
- Compiler Intrinsic only for variables / struct declaration
  - GCC/Clang: `__attribute__((aligned(N)))`
  - MSVC: `__declspec(align(N))`
- Compiler Intrinsic for dynamic pointer
  - GCC/Clang: `__builtin_assume_aligned(x)`
  - Intel: `__assume_aligned(x)`

```cpp
struct alignas(16) A1 { // C++11
    int x, y;
};

struct __attribute__((aligned(16))) A2 { // compiler-specific attribute
    int x, y;
};

auto ptr1 = new int[100, 16]; // 16B alignment, C++17
auto ptr2 = new int[100];      // 4B alignment guarantee
auto ptr3 = __builtin_assume_aligned(ptr2, 16); // compiler-specific attribute
auto ptr4 = new A1[10];        // no aligment guarantee
```

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

Hardware Notes

- Instruction throughput greatly depends on processor model and characteristics
- 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 $\rightarrow$ cache/memory efficiency

Operations

- In modern architectures, arithmetic increment/decrement `++` / `--` has the same performance of `add` / `sub`

- **Prefer prefix operator** (`++var`) instead of the postfix operator (`var++`) *

- Use the **compound operators** (`a += b`) instead of operators combined with assignment (`a = a + b`) *

- **Keep near constant values/variables** → the compiler can merge their values

* the compiler automatically applies such optimization whenever possible (this is not ensured for object types)

Integer Multiplication

Integer multiplication requires double the number of bits of the operands

```
// 32-bit PLATFROM

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

int64_t f2(int64_t 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!!
}
```

Power-of-Two Multiplication/Division/Modulo

- Prefer shift for **power-of-two multiplications** (`a << b`) and **divisions** (`a >> b`) only for run-time values *
- Some **`unsigned`** operations are faster than **`signed`** operations (deal with negative number), e.g. `x / 2`
- 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)

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

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;
}
```

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/

Using intrinsic instructions is <u>extremely dangerous</u> 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`

Why is the standard "abs" function faster than mine?

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)

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

Make your lookup table do more

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

Branches are expensive 1/2

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 instead of 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`
- Prefer **square brackets** syntax `[]` over pointer arithmetic operations for array access to facilitate compiler loop optimizations (polyhedral loop transformations)
- Prefer **signed integer** for **loop indexing**. The compiler optimizes more aggressively such loops since integer overflow is not defined
- Prefer range-based loop for iterating over a container [1]

---

[1] The Little Things: Everyday efficiencies

- In general, `if` statements affect performance when the branch is taken
- Some compilers (e.g. `clang`) use assertion for optimization purposes: most likely code path, not possible values, etc. [2]
- 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 [3] (see next slides)

[1] Branch predictor: How many 'if's are too many?
[2] Andrei Alexandrescu
[3] 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

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 2/2

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`, and `clang` compilers (but not `GCC`) provide the preprocessing directive `#pragma unroll` (to insert above the loop) to force loop unrolling. The compiler already applies the optimization in most cases

`Why are unrolled loops faster?`

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;
}
```

Compiler Hints - `[[assume]]`

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
```

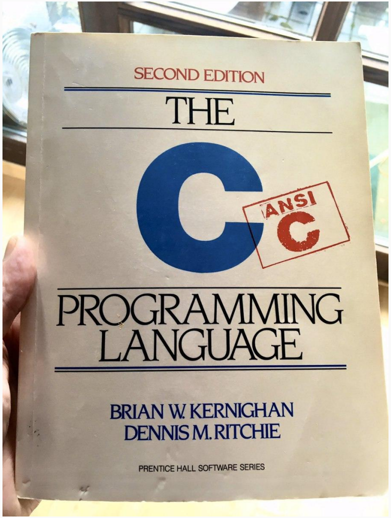
Some compilers define `__builtin_assume_aligned(ptr, aligment)` to assume that the returned pointer is at least `aligment` bytes aligned, and optimize the memory accesses

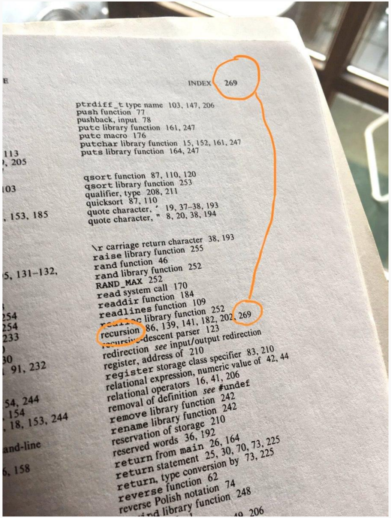
Avoid run-time recursion (very expensive). Prefer *iterative* algorithms instead (see next slides)

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





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

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

pass by-value Small data types ($\leq 8/16$ bytes)
The data are copied into registers, instead of stack
It avoids aliasing performance issues

pass by-pointer Introduces one level of indirection
They should be used only for raw pointers (potentially `NULL`)

pass by-reference *May not* introduce one level of indirection if related in the same translation unit/LTO
`pass-by-reference` is more efficient than `pass-by-pointer` as 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 - Active Objects 2/3

For *active* objects with non-trivial copy constructor or destructor:

by-value Could be very expensive, and hard to optimize

by-pointer/reference Prefer pass-by-`const`-pointer/reference

`const` function member overloading can also be cheaper

Argument Passing - Passive Objects 3/3

For *passive* objects with trivial copy constructor *and* destructor:

by-value/by-reference Most compilers optimize **pass by-value** with **pass by-reference** and **the opposite case** for *passive* data structures if related to the same translation unit/LTO

by-const-value Always produce the optimal code if applied in the same translation unit/LTO. It is converted to `pass-by-const ref` if needed
In general, it should be avoided for as it does not change the function signature

by-value Doesn't always produce the optimal code for large data structures

by-reference Could introduce a level of indirection

Function Optimizations

- *Keep small the number of function parameters*. The parameters can be passed by using the registers instead filling and emptying the stack
- Consider *combining several function parameters* in a structure
- `const` modifier applied to pointers and references *does not produce better code* in most cases, but it is useful for ensuring read-only accesses
- `__attribute__(pure)` attribute (Clang, GCC) specifies that a function has no side effects on its parameters
- `__attribute__(const)` attribute (Clang, GCC) specifies that a function has no side effects on its parameters and global variables

GoTW#81: Constant Optimization?

`inline` Function Declaration 1/2

inline (internal linkage)

`inline` specifier when applied to internal linkage functions (`static` or `anonymous namespace`) is a hint for the compiler.

The code of the function can be copied where it is called (*inlining*)

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

- It is just a hint for the compiler that can ignore it (`inline` increases the compiler heuristic threshold)
- `inline` 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:

```
__attribute__((always_inline)) void f() { ... }
__attribute__((noinline))      void f() { ... }
```

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

Local Functions

All compilers, except MSVC, export all function symbols → slow, the symbols can be used in other translation units

Alternatives:

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

gcc.gnu.org/wiki/Visibility

Pointers Aliasing

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

Benchmarking matrix multiplication

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

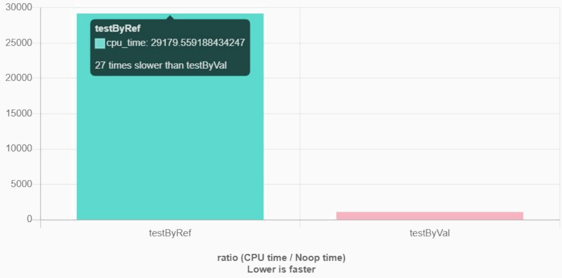
```
void matrix_mul_v2(const int* __restrict A,
                   const int* __restrict B,
                   int                   N,
                   int*       __restrict C) {
```

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

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

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

Object RAII 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)
- Ensure defaulted default and copy constructors `= default` 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: **exceptions**(and use `noexcept`), **`dynamic_cast`**, **smart pointer**

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

Object Operation Optimizations

- Use `static` for all members that do not use instance member (avoid passing `this` pointer)

- Avoid multiple `+` operations between objects to avoid temporary storage

- Prefer `++obj` / `--obj` (return `&obj`), instead of `obj++`, `obj--` (return old `obj`)

- Prefer `x += obj`, instead of `x = x + obj` → avoid the object copy

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
```