

Modern C++ Programming

16. CODE OPTIMIZATION I

Federico Busato

University of Verona, Dept. of Computer Science
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- Memory Mapped I/O
- Speed Up Raw Data Loading

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- Memory Hierarchy
- Memory Locality
- Internal Structure Alignment
- External Structure Alignment

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3 Locality and Memory Access Patterns

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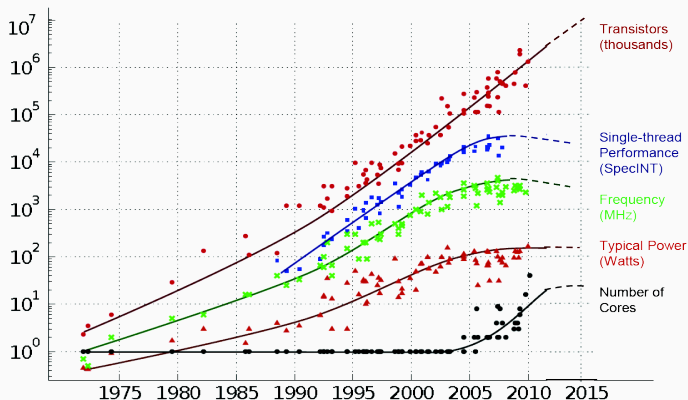
7 C++ Objects

- C++ Objects Optimizations

Gordon Moore, Intel co-founder



The Moore's Law is not (yet) dead but the same concept is not true for clock frequency, single-thread performance, and power consumption. How we can provide value?



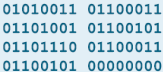


Reasons for Optimizing

- In the first decades, the *computer performance was extremely limited*. Low-level optimizations were essential to fully exploit the hardware
- Modern systems provide much higher performance, but *we cannot more rely on hardware improvement* on short-period
- Performance and efficiency add market value (fast program for a given task), e.g. search, page loading, etc.
- Optimized code uses less resources, e.g. in a program that runs on a server for months or years, a small reduction in the execution time translates in a big saving of power consumption

The Role of Software Engineering and Algorithms

Forget Moore's Law. Algorithms drive technology forward

"Algorithmic improvements make more efficient use of existing resources and allow computers to do a task faster, cheaper, or both. Think of how easy the smaller MP3 format made music storage and transfer. That compression was because of an algorithm."

Technology			
	Software	Algorithms	Hardware architecture
	Software performance engineering	New algorithms	Hardware streamlining
Opportunity	Removing software bloat	New problem domains	Processor simplification
	Tailoring software to hardware features	New machine models	Domain specialization
Examples			

- Forget Moore's Law
- What will drive computer performance after Moore's law?

Going the Other Way

- Computing systems are unfathomably complex
- Optimization is complicated and surprising
- Doing something sensible had opposite effect
- We often try clever things that don't work

- How about trying something silly then?

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from *"Speed is Found in the Minds of People"*,
Andrei Alexandrescu, CppCon 2019

- `Optimized C++`, *Kurt Guntheroth*
- `Awesome C/C++ performance optimization resources`, *Bartłomiej Filipek*
- `Optimizing C++`, *wikibook*
- `Optimizing software in C++`, *Agner Fog*
- `Hacker Delight (2nd)`, *Henry S. Warren*

General Concepts

The **asymptotic analysis** refers to estimate the execution time or memory usage as function of the input size (the *order of growing*)

The *asymptotic behavior* is opposed to a *low-level analysis* of the code (instruction/loop counting/weighting, cache accesses, etc.)

Drawbacks:

- The *worst-case* is not the *average-case*
- Asymptotic complexity does not consider small inputs (think to *insertion sort*)
- The hidden constant can be relevant in practice
- Asymptotic complexity does not consider instructions cost and hardware details

Be aware that only **real-world problems** with a small asymptotic complexity or small size can be solved in a “*user*” *acceptable time*

Three examples:

- *Sorting*: $\mathcal{O}(n \log n)$, try to sort an array of one billion elements (4GB)
- *Diameter of a (sparse) graph*: $\mathcal{O}(V^2)$, just for graphs with a few hundred thousand vertices it becomes impractical without advanced techniques
- *Matrix multiplication*: $\mathcal{O}(N^3)$, even for small sizes N (e.g. 8K, 16K), it requires special accelerators (e.g. GPU, TPU, etc.) for achieving acceptable performance

Time-Memory Trade-off

The **time-memory trade-off** is a way of solving a problem or calculation in less time by using more storage space (less often the opposite direction)

Examples:

- *Memoization* (e.g. used in dynamic programming): returning the cached result when the same inputs occur again
- *Hash table*: number of entries vs. efficiency
- *Lookup tables*: precomputed data instead branches
- *Uncompressed data*: bitmap image vs. jpeg

"If you're not writing a program, don't use a programming language"

Leslie Lamport, Turing Award

"First solve the problem, then write the code"

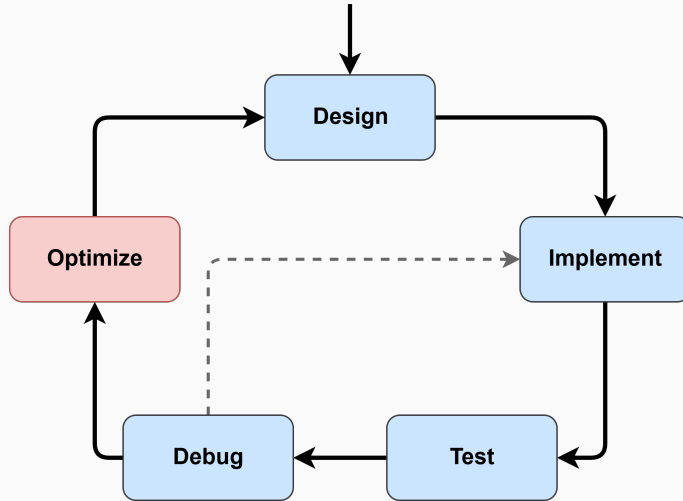
"Inside every large program is an algorithm trying to get out"

Tony Hoare, Turing Award

"Premature optimization is the root of all evil"

Donald Knuth, Turing Award

"Code for correctness first, then optimize!"



- One of the most important phase of the optimization cycle is the **application profiling** for finding regions of code that are *critical for performance* (**hotspot**)
 - Expensive code region (absolute)
 - Code regions executed many times (cumulative)
- Most of the times, **there is no the perfect algorithm for all cases** (e.g. insertion, merge, radix sort). Optimizing refers also in finding the correct heuristics for different program inputs instead of modifying the existing code

Ahmdal Law

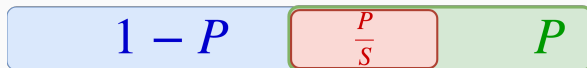
The **Ahmdal law** expresses the maximum improvement possible by improving a particular part of a system

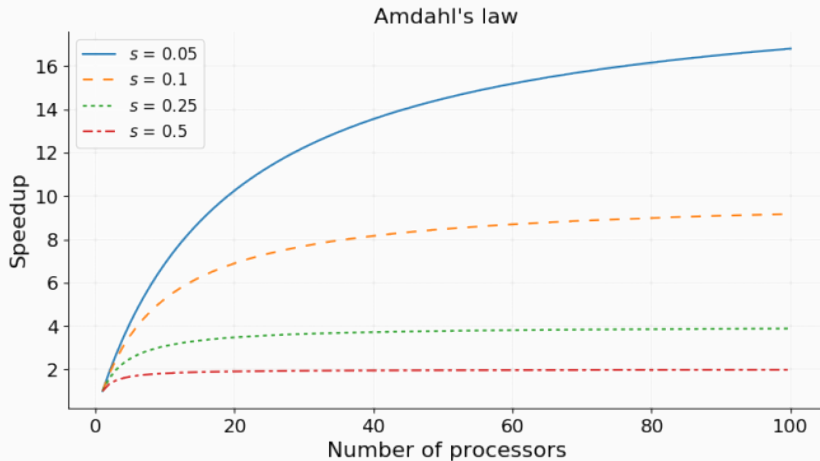
Observation: The performance of any system is constrained by the speed or capacity of the slowest point

$$\text{Improvement}(S) = \frac{1}{(1 - P) + \frac{P}{S}}$$

P : portion of the system that can be improved

S : improvement factor





note: s is the portion of the system that cannot be improved

Throughput, Bandwidth, Latency

The **throughput** is the rate at which operations are performed

Peak throughput:

$(\text{CPU speed in Hz}) \times (\text{CPU instructions per cycle}) \times$
 $(\text{number of CPU cores}) \times (\text{number of CPUs per node})$

NOTE: modern processors have more than one computation unit

The **memory bandwidth** is the amount of data that can be loaded from or stored into a particular memory space

Peak bandwidth:

$(\text{Frequency in Hz}) \times (\text{Bus width in bit} / 8) \times (\text{Pump rate (memory type multiplier)})$

The **latency** is the amount of time needed for an operation to complete

The performance of a program is *bounded* by one or more aspects of its computation. This is also strictly related to the underlying hardware

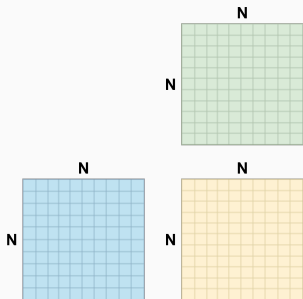
- **Memory-bound.** The program spends its time primarily in performing *memory accesses*. The progress is limited by the *memory bandwidth* (sometime memory-bound also refers to the amount of memory available)
- **Compute-bound.** The program spends its time primarily in computing *arithmetic instructions*. The progress is limited by the *speed of the CPU*

- **Latency-bound.** The program spends its time primarily in waiting *the data are ready* (instruction/memory dependencies). The progress is limited by the *latency of the CPU/memory*
- **I/O Bound.** The program spends its time primarily in performing *I/O operations* (network, user input, storage, etc.). The progress is limited by the *speed of the I/O subsystem*

Arithmetic Intensity

Arithmetic/Operational Intensity is the ratio of total operations to total data movement (bytes or words)

The naive matrix multiplication algorithm requires $N^3 \cdot 2$ floating-point operations (multiplication + addition), while it involves $(N^2 \cdot 4B) \cdot 3$ data movement



$$R = \frac{\text{ops}}{\text{bytes}} = \frac{2n^3}{12n^2} = \frac{n}{6}$$

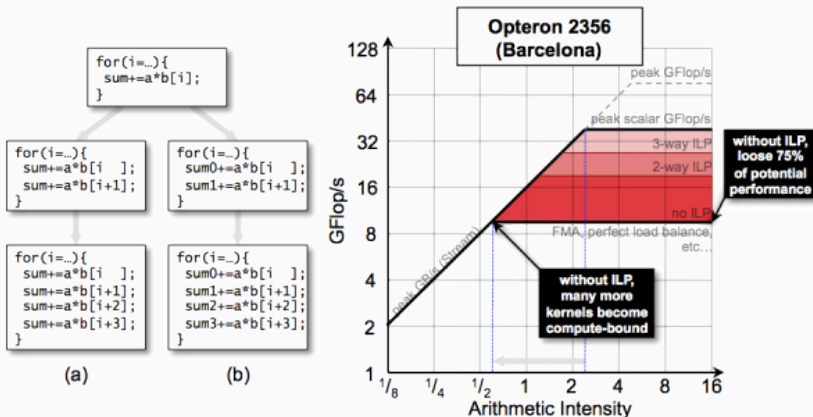
which means that for every byte accessed, the algorithm performs $\frac{n}{6}$ operations \rightarrow **compute-bound**

N	Operations	Data Movement	Ratio	Exec. Time
512	$268 \cdot 10^6$	3 MB	85	2 ms
1024	$2 \cdot 10^9$	12 MB	170	21 ms
2048	$17 \cdot 10^9$	50 MB	341	170 ms
4096	$137 \cdot 10^9$	201 MB	682	1.3 s
8192	$1 \cdot 10^{12}$	806 MB	1365	11 s
16384	$9 \cdot 10^{12}$	3 GB	2730	90 s

A modern CPU performs 100 GFlops, and has about 50 GB/s memory bandwidth

Roofline Model

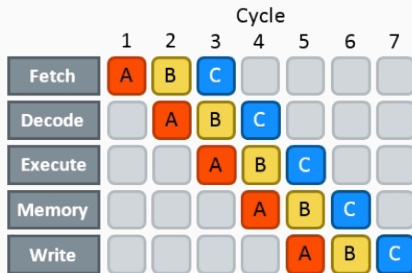
The **Roofline model** is a visual performance model used to provide performance estimates of a given application by showing hardware limitations, and potential benefit and priority of optimizations



Modern processor architectures are deeply pipelined → superscalar processor

Instruction-Level Parallelism (ILP) is a measure of how many instructions in a computer program can be executed simultaneously by issuing *independent* instructions in sequence (*out-of-order*)

Instruction pipelining is a technique for implementing ILP within a single processor



Microarchitecture	Pipeline stages
Core	14
Bonnell	16
Sandy Bridge	14
Silvermont	14 to 17
Haswell	14
Skylake	14
Kabylake	14

The pipeline efficiency is affected by

- **Instruction stalls**, e.g. cache miss, an execution unit not available, etc.
- **Bad speculation**, branch misprediction

```
for (int i = 0; i < N; i++) // with no optimizations, the loop  
    C[i] = A[i] * B[i];      // is executed in sequence
```

can be rewritten as:

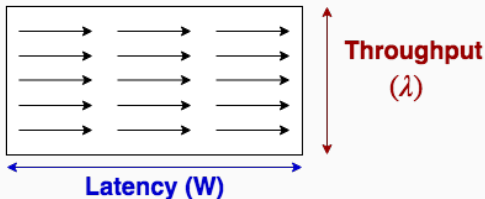
```
for (int i = 0; i < N; i += 4) { // four independent  
    C[i]      = A[i]      * B[i]; // multiplications  
    C[i + 1] = A[i + 1] * B[i + 1]; // per iteration  
    C[i + 2] = A[i + 2] * B[i + 2];  
    C[i + 3] = A[i + 3] * B[i + 3];  
}
```

ILP and Little's Law

The **Little's Law** expresses the relation between *latency* and *throughput*. The *throughput* of a system λ is equal to the number of elements in the system divided by the average time spent (*latency*) W for each elements in the system:

$$L = \lambda W \rightarrow \lambda = \frac{L}{W}$$

- L : average number of customers in a store
- λ : arrival rate (*throughput*)
- W : average time spent (*latency*)



Data-Level Parallelism

Data-Level Parallelism refers to the execution of the same operation on multiple data in parallel

Vector processors or *array processors* provide SIMD (*Single Instruction-Multiple Data*) or vector instructions for exploiting data-level parallelism

The popular vector instruction sets are:

MMX *MultiMedia eXtension*. 80-bit width (Intel, AMD)

SSE (SSE2, SSE3, SSE4) *Streaming SIMD Extensions*. 128-bit width (Intel, AMD)

AVX (AVX, AVX2, AVX-512) *Advanced Vector Extensions*. 512-bit width (Intel, AMD)

NEON *Media Processing Engine*. 128-bit width (ARM)

SVE (SVE, SVE2) *Scalable Vector Extension*. 128-2048 bit width (ARM)

Thread-Level Parallelism

A **thread** is a single sequential execution flow within a program with its state (instructions, data, PC, register state, and so on)

Thread-level parallelism refers to the execution of separate computation “*thread*” on different processing units

The **Instruction Set Architecture** (ISA) is an abstract model of the CPU to represent its behavior. It consists of addressing modes, instructions, data types, registers, memory architecture, interrupt, etc.

It does not defined how an instruction is processed

The **microarchitecture** (μ arch) is the implementation of an **ISA** which includes pipelines, caches, etc.

Complex Instruction Set Computer (CISC)

- Complex instructions for special tasks even if used infrequently
- Assembly instructions follow software. Little compiler effort for translating high-level language into assembly
- Initially designed for saving cost of computer memory and disk storage (1960)
- High number of instructions with different size
- Instructions require complex micro-ops decoding (translation) for exploiting ILP
- Multiple low-level instructions per clock but with high latency

Hardware implications

- High number of transistors
- Extra logic for decoding. Heat dissipation
- Hard to scale

Reduced Instruction Set Computer (RISC)

- Simple instructions
- Small number of instructions with fixed size
- 1 clock per instruction
- Assembly instructions does not follow software
- No instruction decoding

Hardware implications

- High ILP, easy to schedule
- Small number of transistors
- Little power consumption
- Easy to scale

CISC Instruction Set

x86 Instruction set

```
MOV AX, 15; AH = 00, AL = 0Fh  
AAA; AH = 01, AL = 05  
RET
```

ARM Instruction set

```
MOV R3, # 10  
AND R2, R0, # 0xF  
CMP R2, R3  
IT LT  
BLT elsebranch  
ADD R2, # 6  
ADD R1, #1  
elsebranch:  
END
```

CISC vs. RISC

- **Hardware market:**

- *RISC* (ARM, IBM): Qualcomm Snapdragon, Amazon Graviton, Nvidia Grace, Nintendo Switch, Fujitsu Fukaku, Apple M1, Apple Iphone/Ipod/Mac, Tesla Full Self-Driving Chip, PowerPC
- *CISC* (Intel, AMD): all x86-64 processors

- **Software market:**

- *RISC*: Android, Linux, Apple OS, Windows OS
- *CISC*: Windows, Linux

- **Power consumption:**

- *CISC*: Intel i5 10th Generation: 64W
- *RISC*: Arm-based smartphone < 5W

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

```
#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 the format string `%s\n` is converted to a `puts()` call

```
printf("%s\n", string);
```
- A `printf` call with a simple format string ending with `\n` is converted to a `puts()` call

```
printf("Hello World\n");
```
- No optimization if the string is not ending with `\n`
- No optimization if 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 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

Another alternative is **Facebook zstd**

github.com/facebook/zstd

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

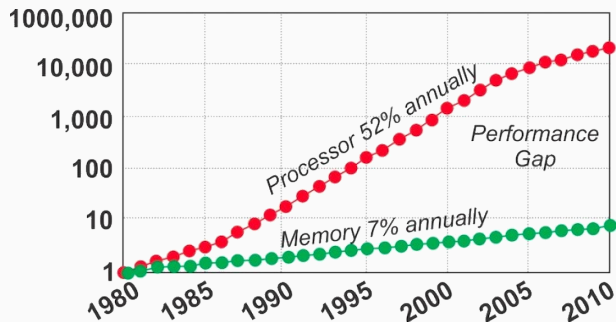
Load Method	Exec. Time	Speedup
ifstream	102 667 ms	1.0x
memory mapped + parsing (first run)	30 235 ms	3.4x
memory mapped + parsing (second run)	22 509 ms	4.5x
memory mapped + lz4 (first run)	3 914 ms	26.2x
memory mapped + lz4 (second run)	1 261 ms	81.4x

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

Locality and Memory Access Patterns

Access to memory dominates other costs in a processor

The Memory Wall:



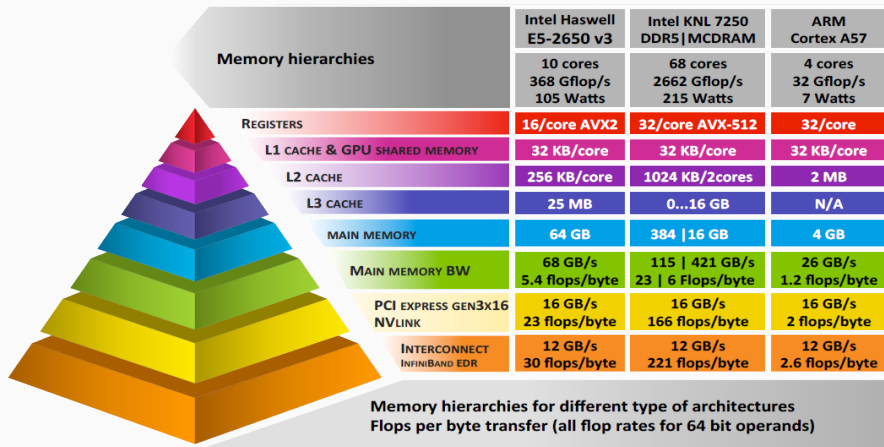
Modern architectures rely on complex memory hierarchy (primary memory, caches, registers, scratchpad memory, etc.). Each level has different characteristics and constrains (size, latency, bandwidth, concurrent accesses, etc.)



1 byte of RAM (1946)



IBM 5MB hard drive (1956)



Source:

*"Accelerating Linear Algebra on Small Matrices from Batched BLAS to Large Scale Solvers",
ICL, University of Tennessee*

Intel Coffee Lake Core-i7-8700 example:

Cache level	Size	Latency	Bandwidth
L1 cache	192 KB	~ 1.5 ns	~ 1,600 GB/s
L2 cache	1.5 MB	~ 4 ns	~ 570 GB/s
L3 cache	12 MB	~ 12 - 40 ns	~ 320 GB/s
DRAM	/	~ 60 ns	~ 40 GB/s
Disk (swap)	/	~ 4-8 ms	~ 2 GB/s

- en.wikichip.org/wiki/WikiChip
- Memory Bandwidth Napkin Math

Memory Locality

- **Spatial Locality** refers to the use of data elements within relatively close storage locations e.g. scan arrays in increasing order, matrices by row. It involves mechanisms such as *memory prefetching* and *access granularity*
- **Temporal Locality** refers to the reuse of specific data within a relatively small time duration, and, as consequence, exploit lower levels of the memory hierarchy (caches), e.g. multiple sparse accesses
Heavily used memory locations can be accessed more quickly than less heavily used locations

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;  
    }  
}
```

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

Cache Optimization Example

Speeding up a random-access function

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

```
for (int i = 0; i < N; i++) {    // V2
    for (int K = 0; K < N; K += CACHE) {
        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)

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

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:

- 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

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 (byte 65)  
}
```

```
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 (byte 40)  
}
```

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)

External Structure Alignment and Padding

Considering the previous example for the structure `A2`, random loads from an array of structure `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`. It can be also extended to 2D (or N -D) data structures such as dense matrices
- **Align keyword or attribute** allows specifying the alignment requirement of a type or an object (next slide)

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)`

Data alignment is essential for exploiting hardware vector instructions (SIMD) like SSE, AVX, etc.

```
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
auto ptr2 = new int[100];      // 4B alignment guarantee
auto ptr3 = __builtin_assume_aligned(ptr2, 16); // compiler-specific attribute
```

Arithmetic

- Instruction throughput greatly depends on processor model and characteristics
- *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)
- Modern processors provide separated units for floating-point computation (FPU)

- **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

- 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 **assignment composite** 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
- Cast one of the two operands to a bigger integer has no cost

```
// gcc -m32 (32-bit system)
int f1(int x, int y) {
    return x * y; // efficient
}

int64_t f2(int x, int y) {
    return x * static_cast<int64_t>(y); // efficient!!
}

int64_t f3(int64_t x, int64_t y) {
    return x * y; // slow
}
```

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 *
- Some **unsigned** operations are faster than **signed** operations (deal with negative number), e.g. $x / 2$
- 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 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 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 an hardware instruction

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

```
rotate left : std::rotrl
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)
// - ensure that "B - A" is not less than zero
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];
}
```

Basic Bit Manipulation

```
x ^ 0 == x
```

```
x ^ ~0 == ~x
```

```
-x == two-complement == ~x + 1
```

```
x & -x           // get the least significant bit
```

```
x | -x           // set one after the least significant bit
```

```
(x & (x - 1))     // clear the least significant bit
```

```
x ^ (x & (x - 1)) // get the least significant bit
```

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`)

Not all control flow instructions involve a `jump` instructions. If the code in the branch is small, the compiler could optimize it in a conditional instruction, e.g. `ccmovl`

- 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` statement
- 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
- Some compilers (e.g. clang) use assertion for optimization purposes: most likely code path, not possible values, etc. ²
- Not all `if` statements (or branches) are translated into jump. Small code section can be optimized in different ways ³ (see next slide)

¹ The Little Things: Everyday efficiencies

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, 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 hoisting can be applied for avoiding redundant initialization

Base case:

```
for (int i = 0; i < 100; i++) {  
    // allocation  
    std::vector v = ...  
    ... // use "v"  
}
```

Better:

```
std::vector s(max_size);  
for (int i = 0; i < 100; i++) {  
    ...  
    v.clear();  
}
```

the compiler already applies such optimization when it is safe (it does not change the program semantic)

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 notes:

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

Branch Hints

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

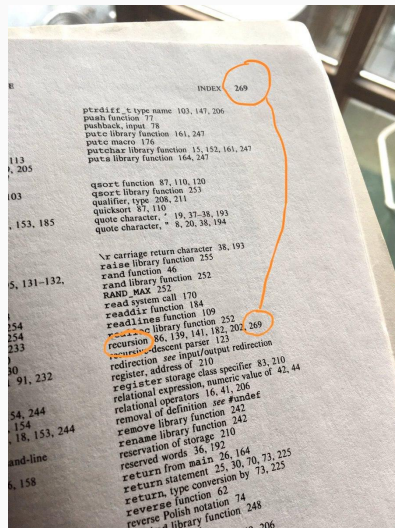
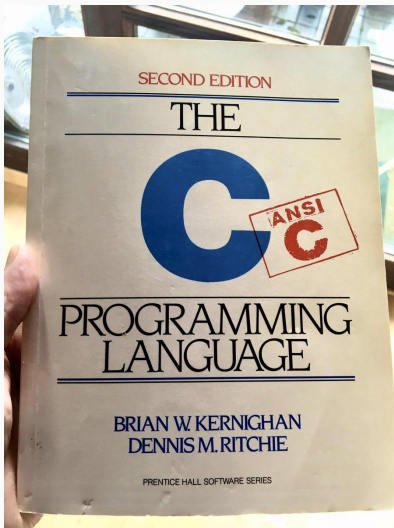
```
for (i = 0; i < 300; i++) {  
    [[unlikely]] if (rand() < 10)  
        return false;  
}
```

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

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 to maintain 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

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

pass by-value small data types ($\leq 8/16$ bytes)

The data are copied into registers, instead of stack

pass by-pointer introduces one level of indirection

They should be used only for raw pointers (potentially NULL)

pass by-reference *may* introduce one level of indirection

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

Most compilers optimize **pass by-value** with **pass by-reference** for *passive* data structures

For *active* objects with non-trivial (and expensive) copy constructor or destructor:

by-value Expensive, hard to optimize

by-pointer/reference ok. Prefer pass-by-`const` -X (`const` overloading can also be cheaper)

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

by-const-value Always produce the optimal code (converted in pass-by-const ref if needed) but it should be avoided for as it does not change the function signature

by-value Produce optimal code except for GCC (tested with GCC 9.2)

by-reference Could introduce a level of indirection

Function Optimizations

- *Pass by-value built-in types and passive data structured (no side-effect).* The compiler already applies heuristics to determine the most efficient way to pass the parameter (by-value or by-reference). Pass by-reference does not allow the compiler to optimize in pass by-value (if not inline)
- *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

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")))`

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 kind of optimization* from code re-ordering to common sub-expression elimination

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

C++ Objects

Variable/Object Scope

Declare local variable in the inner most scope

- the compiler can more likely fit them into registers instead 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;  
}
```

Variable/Object Scope

Exception! Built-in type variables and passive structures should be placed in the inner most 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];  
}
```

- 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)
- Avoid dynamic operations: **exceptions*** (and use `noexcept`), `dynamic_cast`, **smart pointer**
- **Virtual calls** are slower than standard functions
- Mark `final` all `virtual` functions that are not overridden

*Investigating the Performance Overhead of C++ Exceptions

- 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
```