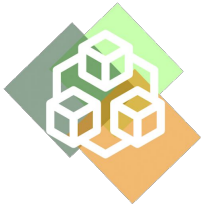
The Performance Price of Virtual Functions

Ivica Bogosavljevic

MUREX

CODE RECKONS

Science to the CORE



About me

- Ivica Bogosavljevic - application performance specialist
- Professional focus is application performance improvement - techniques used to make your C/C++ program run faster by using better algorithms, better exploiting the underlying hardware, and better usage of the standard library, programming language, and the operating system.
- Work as a performance consultant - helping developer teams deliver fast software
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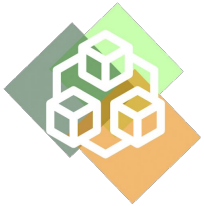
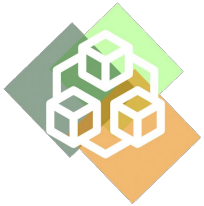


Introduction

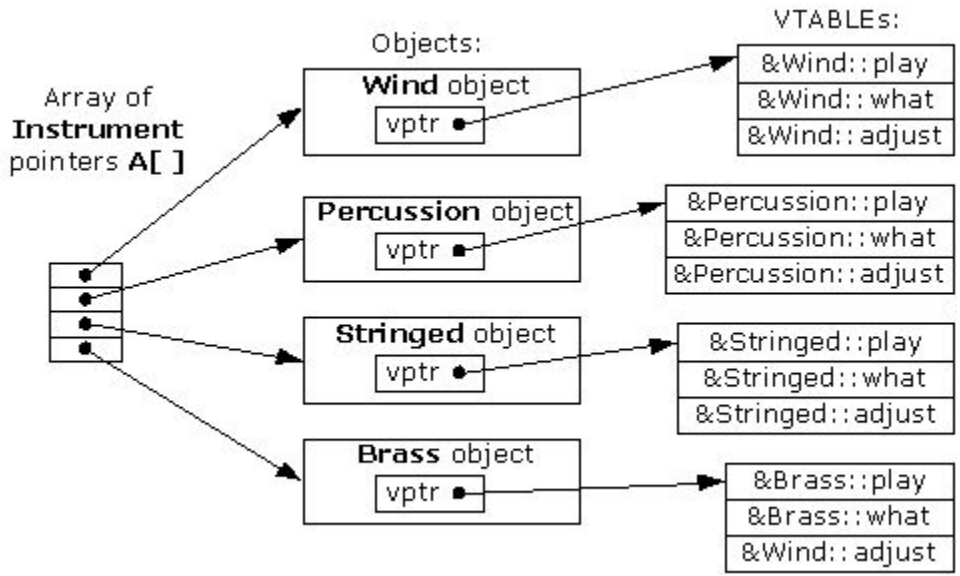
- Virtual functions are the most beloved feature of C++ since they give a great flexibility to the language
- But they come with a performance cost
- As you will see later, the performance cost of virtual functions depends on several factors and it is not easy to pinpoint

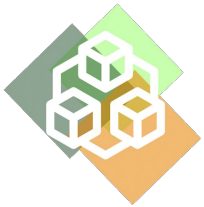


How virtual functions work?

- C++ standard doesn’t mandate implementation of virtual functions
- Most compilers, however, implement virtual functions in the similar manner
  - The address of the function is not known at the compile time and has to be looked up
  - Each type has a virtual function table, and each instance of the type has a pointer to this (shared) table
  - The function position in the table (offset) is know at the compile time
- When the call to the virtual function is made, the program:
  - Follows the instance’s virtual table pointer
  - In the virtual table, it goes to the compile-time defined position and reads the function address
  - It then calls the function

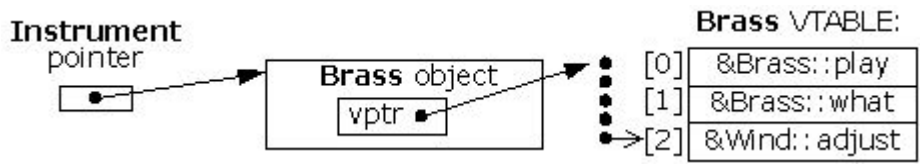
How virtual functions work?

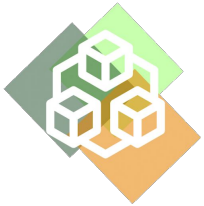




Initial Analysis

- Initially, more work is involved when it comes to calling a virtual function compared to when calling a function whose address is known at compile time
- The compiler just has to perform the jump for non-virtual function to an address known at compile time
- For a call to the virtual function, the program has to access the virtual table pointer

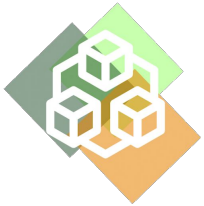




Initial Analysis - experiment

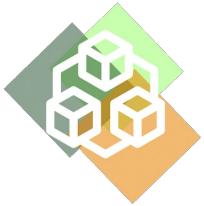
- A vector of 20 million objects of the same type
- 20 million calls to the virtual function vs 20 million calls to the non-virtual function

	Virtual function call	Non-virtual function call
Short and fast function	153 ms	126 ms
Long and slow function	32.090 ms	31.848 ms



Initial Analysis - conclusion

- The results don’t look that bad
- There is a noticeable overhead for small function (18%).
- For the large function, the overhead is negligible
- But is this all there is to virtual functions?

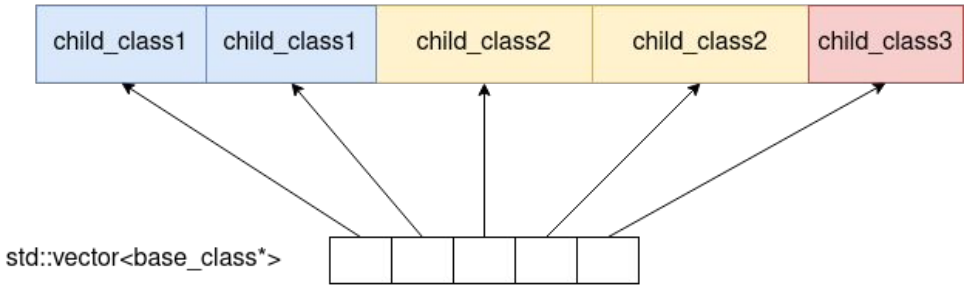


Vector of pointers

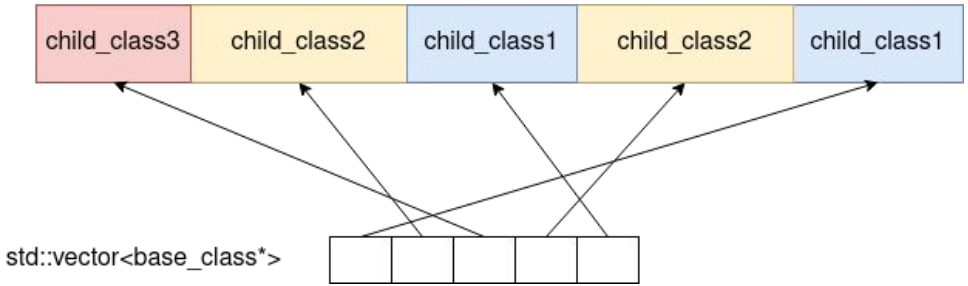
- Virtual dispatching mechanism is activated when we are accessing objects through pointers
- So, to use virtual dispatching, we need to allocate objects on heap
- Accessing objects on the heap can be very slow due to data cache misses
  - If the neighboring pointers do not point to neighboring elements on the heap, the performance can be very poor
  - There is no guarantee that the neighboring pointers will point to neighboring elements on the heap. In fact, as the program becomes bigger and more complex there is less and less chance that this will happen
- Vector of objects is much better for the performance compared to vector of pointers
  - The vector of objects doesn’t suffer from data cache misses

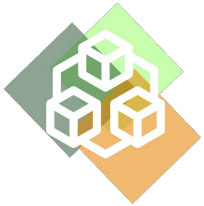
Vector of pointers

Optimal layout



Non-optimal layout

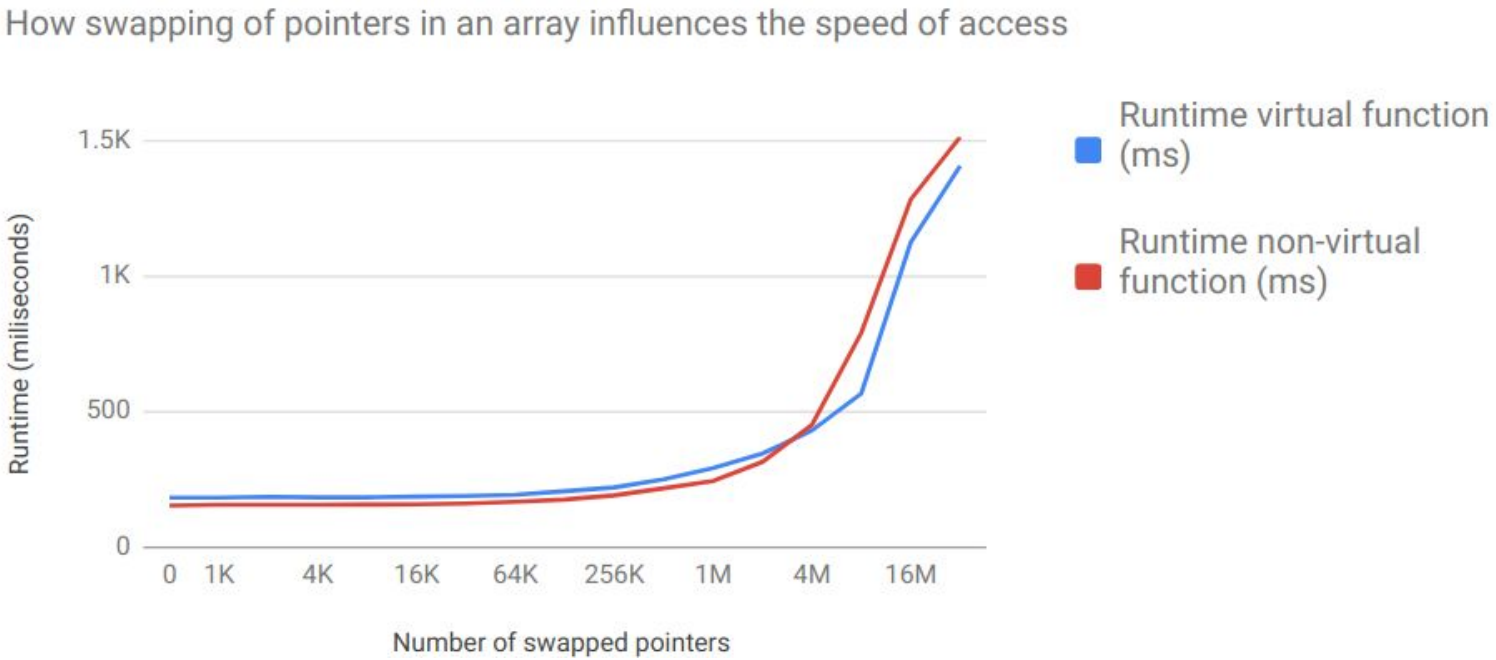


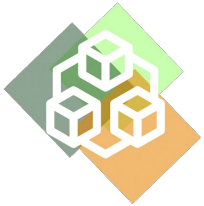


Vector of pointers - experiment

- At the beginning we have a vector of objects containing 20 million objects
- Another vector of pointers, pointer at location *i* points to an object at location *i*
  - This is the perfect ordering: neighboring pointers point to neighboring objects
- We measure the time needed to iterate through 20 million objects by following the pointers in the vector of pointers
- In the next of the experiment, we pick a random pointer in the vector of pointer and swap it with the pointer at place zero
  - Everytime we do this operation, we slow down the iteration a bit

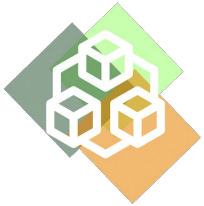
Vector of pointers - results





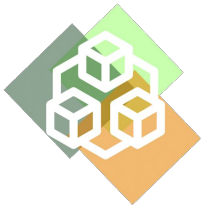
Vector of pointers - conclusion

- Memory layout is tremendously important for program performance
  - Worst case is 7.5 times slower than the fastest case
- The slowdown isn't related to virtual functions per se, it is related to the memory layout
  - Still, the main reason you want to use the vector of pointers to achieve polymorphism
- Alternatives to vector of pointers:
  - Use `std::variant` with `std::visitor`
  - Use polymorphic_vector - uses virtual dispatching, but doesn't uses pointers. Downside is increased memory consumption
  - Use per type vector (e.g. `boost::base_collection`), a very useful if you don't need a specific ordering in the vector



Compiler Optimizations

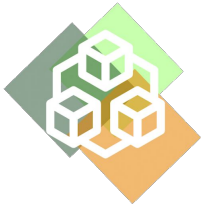
- Compiler knows the address of non-virtual functions at compile time.
  - This means the compiler can inline the non-virtual function and avoid the function call
- Inlining saves a few instructions on the function call, but that is not all
- After inlining, the compiler can perform many other compiler optimizations, e.g:
  - Move loop invariant code outside of the calling loop
  - Use special instructions that can process more than one data at a time in a process called vectorization



Compiler Optimizations - experiment

```
class object {
  protected:
   bool m_is_visible;
   unsigned int m_id;
   static unsigned int m_offset;
  public:
   ATTRNOINLINE
   bool is_visible() { return m_is_visible; }
   ATTRNOINLINE
   unsigned int get_id3() { return m_id + m_offset; };
};
```

```
// Test loop
for (int i = 0; i < arr_len; i++) {
   object* o = pv.get(i);
   if (o->is_visible()) {
       count += o->get_id3();
   }
}
```

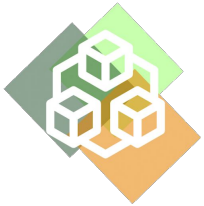


Compiler Optimizations - results

- Measured the performance of non-virtual function, inlined and non-inlined.

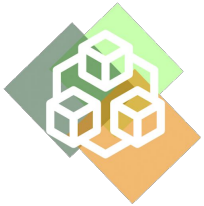
```
// Test loop
for (int i = 0; i < arr_len; i++) {
    object* o = pv.get(i);
    if (o->is_visible()) {
        count += o->get_id3();
    }
}
```

Vector 20M objects	Non-inlined	Inlined
Runtime	242 ms	136



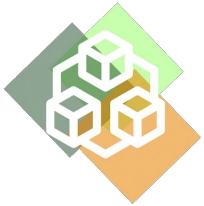
Compiler Optimizations - conclusion

- Virtual functions inhibit compiler optimizations because they are essentially not inlinable
- A solution for this is ***type based processing***
  - Don’t mix the types, each type has its own loop and its own processing
  - The compiler can inline small functions and perform the compiler optimizations
  - Already implemented in boost::base_collection
  - This approach works only if objects in the vector don’t have to be sorted
- The benefits of compiler optimization that happen due to inlining are very case dependent
  - Some code can profit a lot from compiler optimizations, other not so much
  - Smaller functions in principle benefit more



Jump Destination Guessing

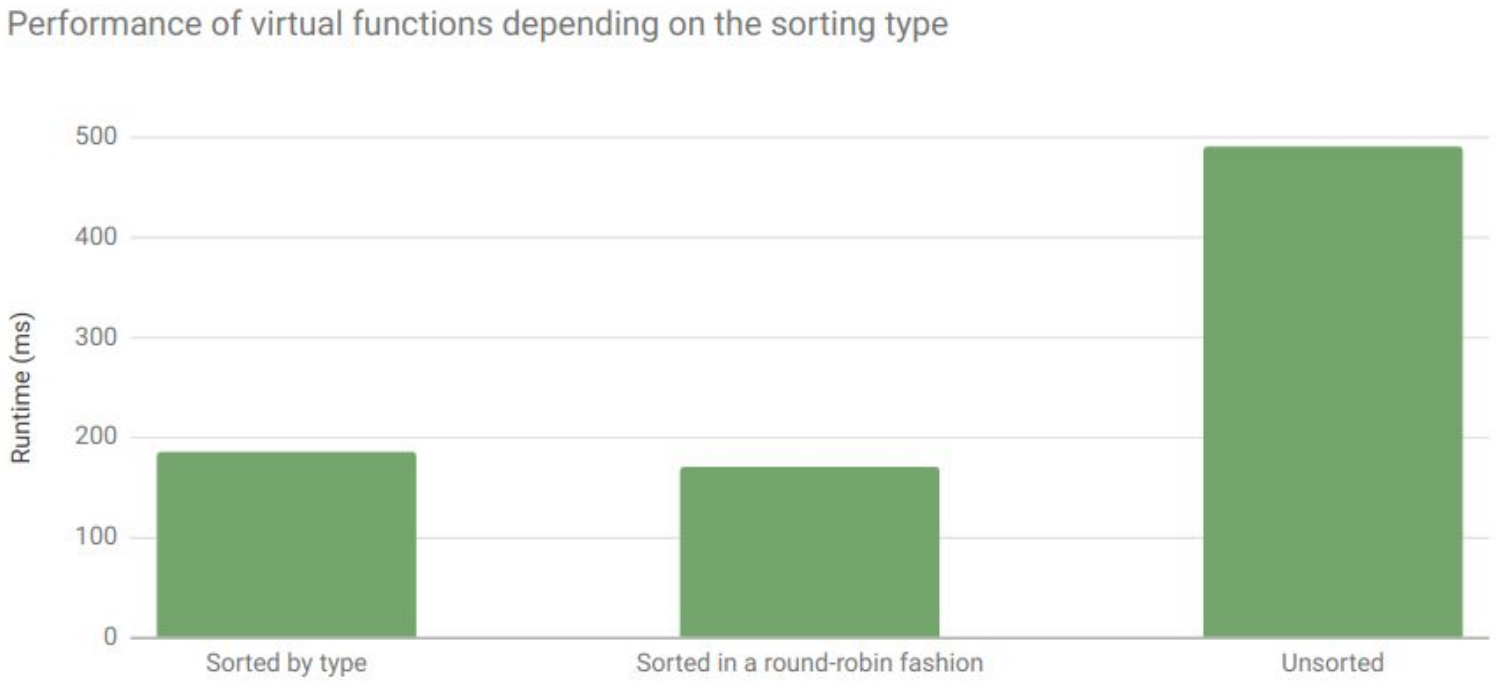
- To speed up computation, modern hardware does a lot of guessing (technical term is *speculative execution*)
- In the case of virtual function, the CPU guesses which virtual function will get called and start executing the instructions belonging to the guessed virtual function
- If the guess is correct, this saves time
- If the guess is wrong, the CPU needs to cancel the effect of wrongly executed instructions and start over
    - This costs time

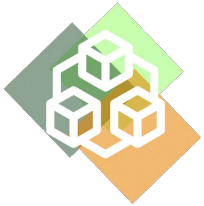


Jump Destination Guessing - experiment

- Three vector of 20 million objects
  - First vector is sorted by type: A, A, A, A, B, B, B, B, C, C, C, C, D, D, D, D
  - Types in vector in predictable fashion: A, B, C, D, A, B, C, D, A, B, C, D, A, B, C, D
  - Types in vector random: B, C, A, C, A, C, B, B, A, C, B, A.
- We measure time needed to call a small virtual function on the three types of vectors

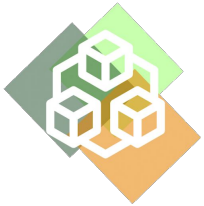
Jump Destination Guessing - results





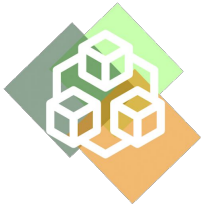
Jump Destination Guessing - conclusion

- If types are sorted in a predictable manner, the CPU can predict the address of the virtual function it needs to call and this speeds up the computation
- If types are unsorted, the CPU cannot guess successfully and precious cycles are lost
  - A solution to this is again, type based processing
  - However, type based processing is not always usable
- The effect is mostly pronounced with short virtual functions



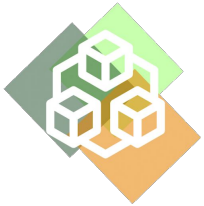
Instruction Cache Evictions

- Modern CPUs rely on “getting to know” the instructions they are executing
- The code that has already been executed is *hot* code
  - Its instructions are in the instruction cache
  - Its branch predictors know the outcome of the branch (true/false)
  - Its jump predictors know the target of the jump
- The CPU is faster when executing hot code compared to executing cold code
- The CPU’s memory is limited
  - The code that is currently hot will eventually become cold unless executed frequently
- Virtual functions, especially large virtual functions where each object has a different virtual function, mean that we are switching from one implementation to another
  - The CPU is constantly switching between different implementations and is always running cold code



Instruction Cache Evictions - experiment

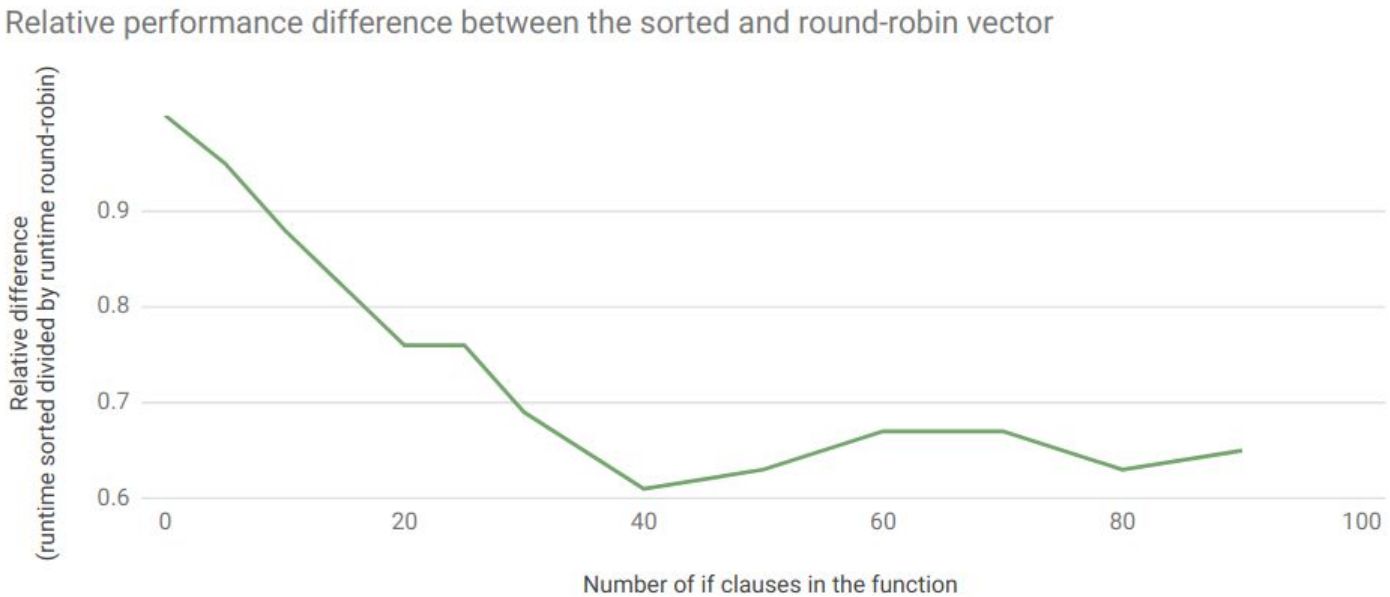
- Measuring the effect of instruction cache eviction is the hardest, because it depends on many factors
  - The number of different virtual function implementations - the bigger the number, the slower the code
  - The number of executed instructions in the virtual functions - the bigger the number, the slower the code
    - The size of virtual function correlates to the number of executed instructions, but they are not the same
  - How sorted are the objects in the container (by type)
    - Best case is when they are sorted by type (AAABBBCCCDDD)
    - Worst case is when they are sorted by type in a round robin fashion (ABCDABCDABCD)



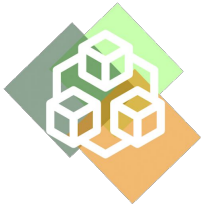
Instruction Cache Evictions - experiment

- Four classes: *rectangle, circle, line* and *monster*
- Four implementations of *long_virtual_functions*
- The *long_virtual_function* consists of a *for* loop with a large *if/elseif/.../else* inside it
- For measurements we use two vectors (20 million objects)
  - Elements of the vector sorted by type: AAABBBCCCDDD
  - Elements of the vector sorted by type in a round-robin fashion:ABCDABCDABCD
- We change the number of comparisons in a large *if/elseif/.../else* block and compare the time needed to iterate the two vectors

Instruction Cache Evictions - result

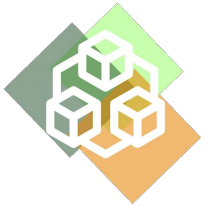


In the worst case, the same function took 7.5 seconds to execute in the sorted vector, and 12.3 seconds to execute in the round-robin vector



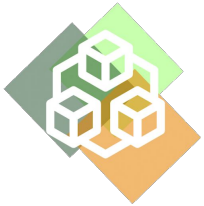
Instruction Cache Eviction - conclusion

- In our example, the cold code was running at the speed of 0.6 of the speed of the fast code
- The phenomenon is not related to the virtual functions themselves
  - It will happen if each instance has a pointer to a different function
- However, it is most likely to occur with large virtual functions on mixed-type unsorted vectors with many different derived types



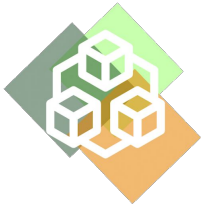
Conclusion

- Virtual functions do not incur too much additional cost by themselves (because of the increased number of executed instructions)
- It is the environment where they run which determines their speed
- The hardware craves predictability: same type, same function, neighboring virtual address
  - When this is true, the hardware run at its fastest
  - It’s difficult to achieve this with casual usage of virtual functions
- In game development, they use another paradigm instead of OOP called: data-oriented design
  - One of its major parts is **type based processing**: each vector holds one type only
    - This eliminates all the problems related to virtual functions
    - However, this approach is not applicable everywhere



Conclusion

- If you need to use virtual functions, bear in mind:
  - The number one factor that is responsible for bad performance are data cache misses
    - Avoiding vector of pointers on a hot path is a must!
  - Other factors also play their role, but to a lesser extend
  - With careful design, you can reap most benefit of virtual functions without incurring too much additional cost
- Here are a few ideas to fix your code with virtual functions:
  - Arrangement of objects in memory is very important!
  - Try to make small functions non-virtual!
    - Most overhead of virtual functions comes from small functions, they cost more to call than to execute
    - Try to keep objects in the vector sorted by type



The End

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