Johny’s Software Lab

# The Performance Price of Virtual Functions

https://johnysswlab.com, @johnysswlab ivica@johnysswlab.com

# About me

- Ivica Bogosavljevic - application performance specialist
- Professional focus is C/C++ application performance improvement:
  - Better algorithms
  - Better exploiting the underlying hardware
  - Better usage of the standard library
  - Better usage of programming language
  - Better usage of the operating system.
- Work as a an external expert
  - If your software is slow, I can help you make it faster
- Writer for software performance blog: Johny’s Software Lab - link in the footer
  - For all the people interested in software performance

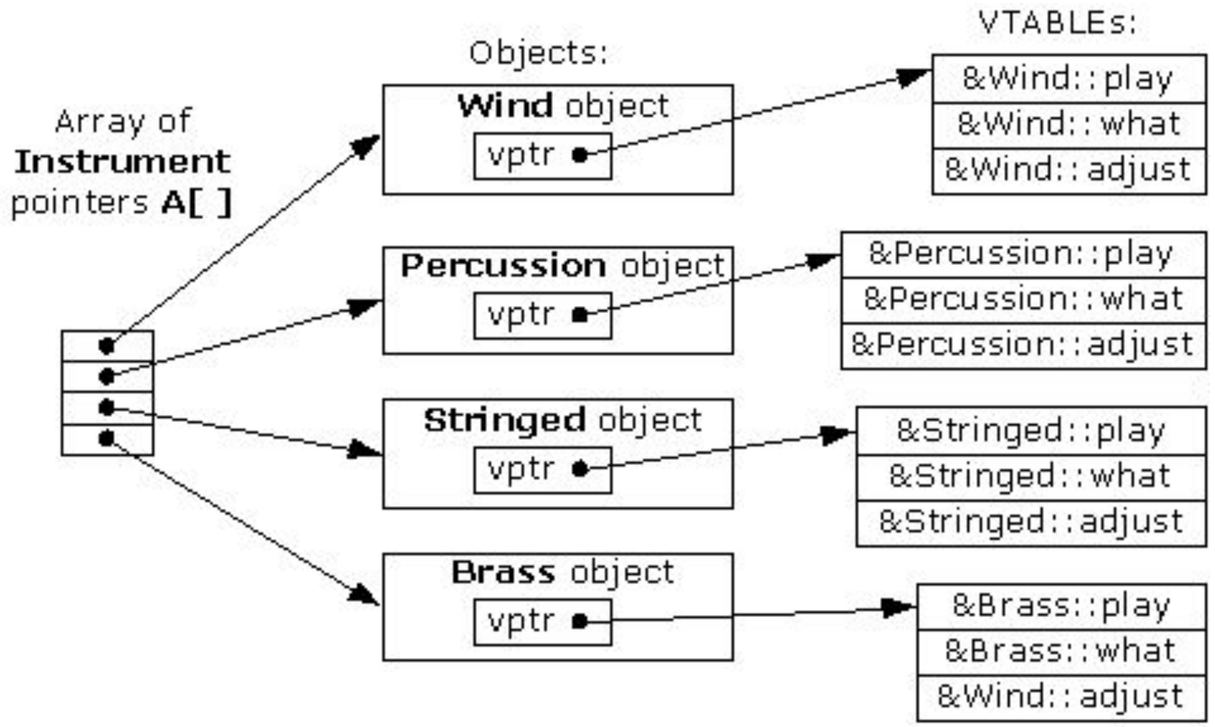
# Introduction

- Virtual functions in C++
  - Enable flexibility
  - The basic component of OOP
- Virtual functions are slower than regular functions
- The performance price of virtual functions depends on several factors
  - Here we explain what are those factors

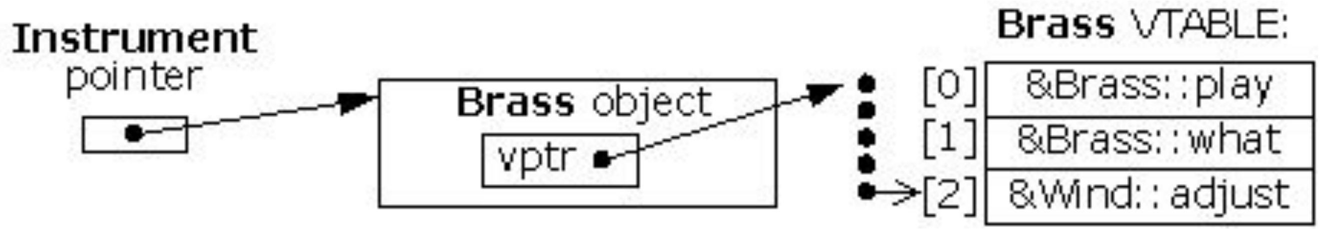
# How virtual functions work?

- C++ standard doesn't mandate implementation of virtual functions
- Most compilers, however, implement virtual functions in a similar manner

# How virtual functions work - virtual tables



# How virtual functions work - function calls



# Initial Analysis

- Virtual functions are more expensive than non-virtual functions
  - The virtual function's address is not known at compile time
  - The program needs to look up the virtual function's address at runtime
  - Virtual function's address lookup is done through 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 |

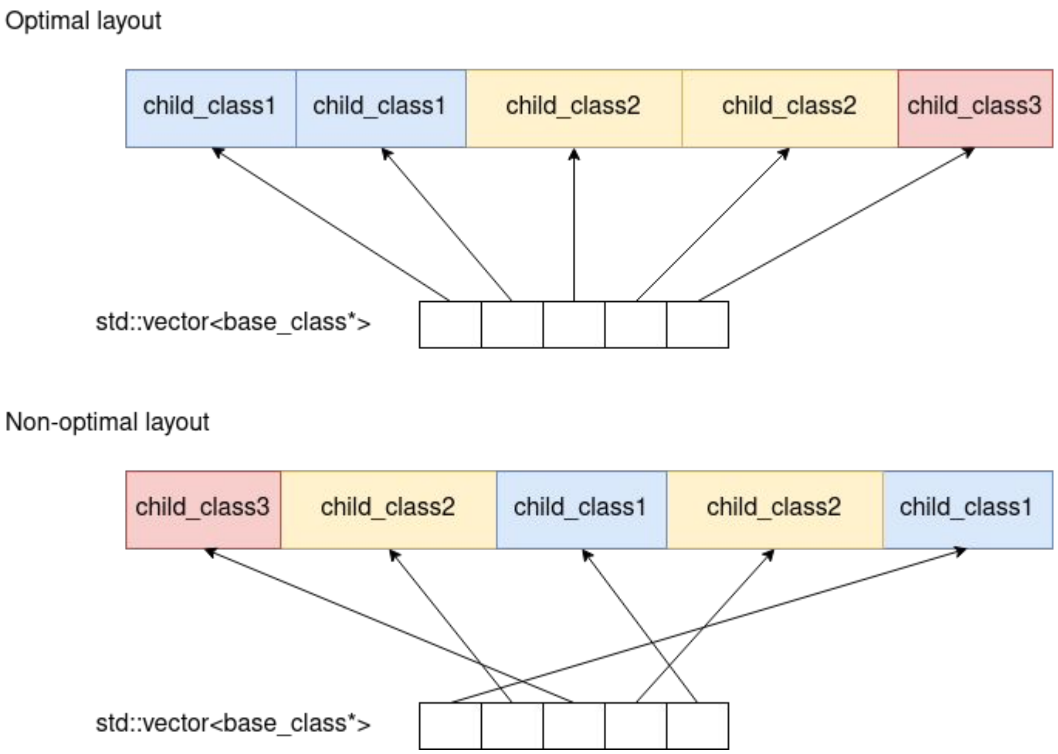
# Initial Analysis - conclusion

- 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

- To activate virtual function mechanism, you need to access the object through a pointer or a reference
  - Objects need to be allocated on the heap (using new, malloc or smart pointers)
- Accessing objects on the heap can be very slow

# Vector of pointers



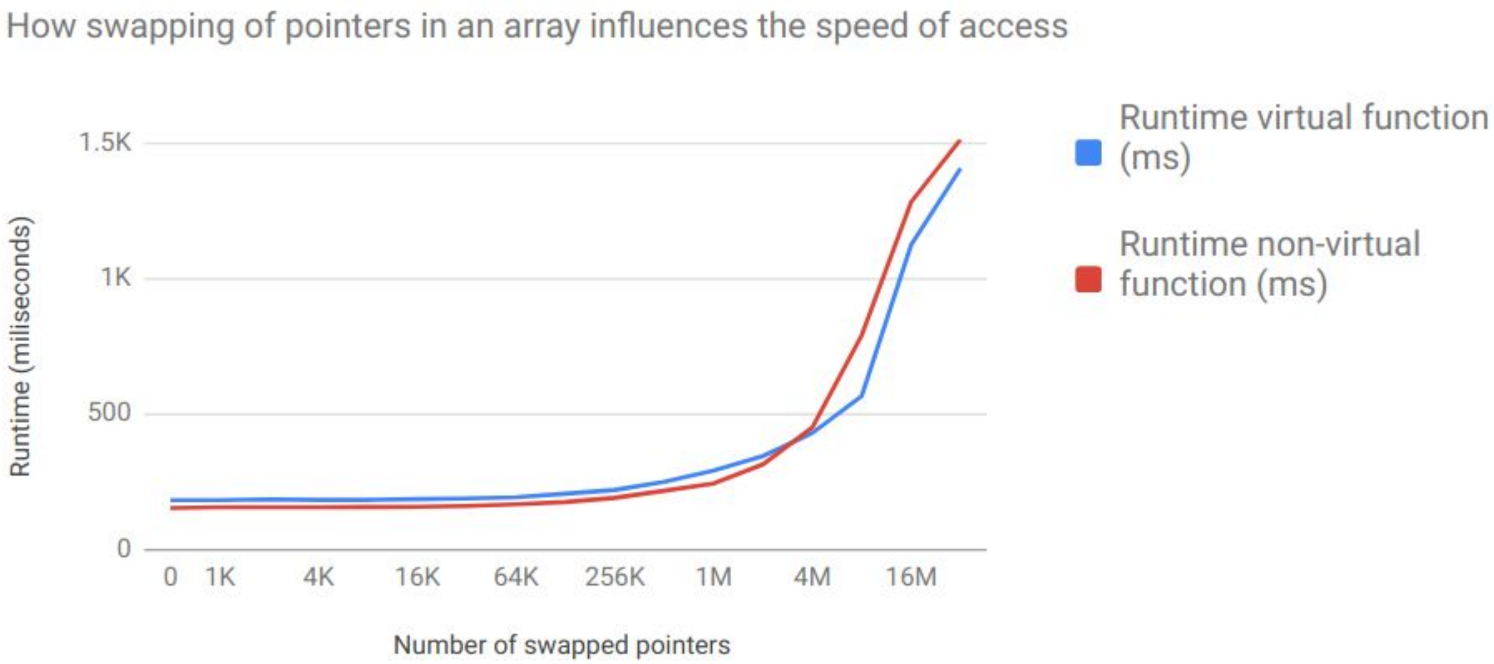
# Vector of pointers

- Accessing objects on the heap can be very slow
  - The reason are data cache misses
  - If objects are neighbors in memory, we can expect performance improvements
  - If objects are not neighbors in memory, we can expect slowdowns
  - If the neighboring pointers do not point to neighboring elements on the heap, we can expect data cache misses
- There is no guarantee that the neighboring pointers will point to neighboring objects in memory
  - 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 - experiment

- 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
  - There are several iterations of the experiment
  - In each new iteration of the experiment, we shuffle the pointer vector a bit
    - Shuffling slows down the traversal a bit
    - We measure the runtime as a function of number of shuffles
    - One shuffle means swap pointer at position [0] with a pointer at position [rand(0, vector_len)]

# Vector of pointers - results



# Vector of pointers - conclusion

- Memory layout is very 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
  - The slowdown 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 → google `polymorphic_vector`
  - 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 <- this can increase speed from 2 to 6 times.

# Compiler Optimizations - Example

```
void my_loop(int arr_len) {
    std::vector<double> in;
    std::vector<double> out;
    …
    for (int i = 0; i < out.size(); i++) {
        out[i] = my_sqrt(in[i]);
    }
}

double my_sqrt(double a) {
    if (debug && a < 0) {
        std::cerr << "Value " << a << "negative\n";
    }
    return std::sqrt(a);
}
```

Loop unswitching

```
void my_loop_inlined(int arr_len) {
    std::vector<double> in;
    std::vector<double> out;
    …
    if (debug) {
        for (int i = 0; i < out.size(); i++) {
            if (in[i] < 0) {
                std::cerr << "Value " << a <<
"negative\n";
            }
            out[i] = std::sqrt(in[i]);
        }
    } else {
        for (int i = 0; i < out.size(); i++) {
            out[i] = std::sqrt(in[i]);
        }
    }
}
```

# 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 ms |

# 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 container and its own loop
  - The compiler can inline small functions and perform the compiler optimizations
  - Already implemented in `boost::base_collection`
  - This approach is applicable 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 profits a lot from compiler optimizations, other not so much
  - Smaller functions in principle benefit more

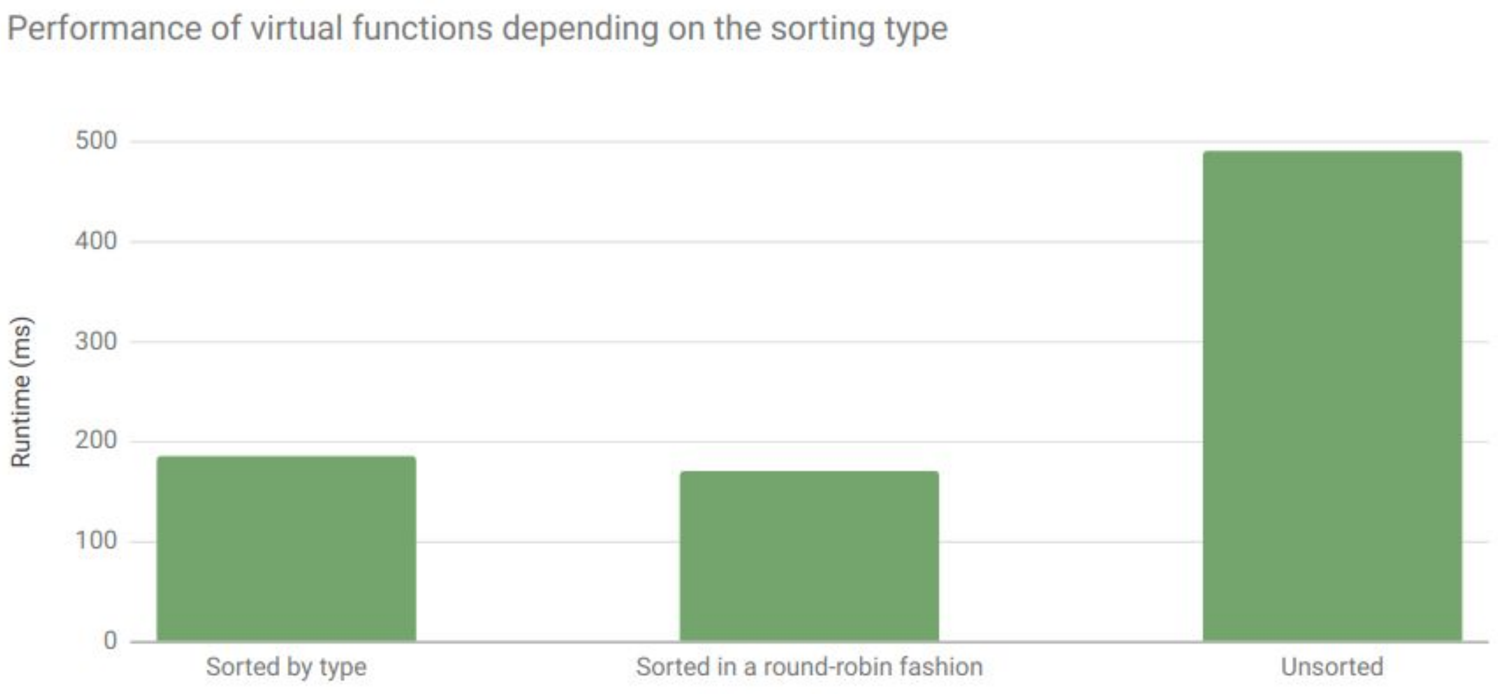
# Jump Destination Guessing

- To speed up computation, modern CPUs do a lot of guessing (technical term is *speculative execution*)
- In the case of virtual function:
  - The CPU guesses which virtual function will get called
  - It starts 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

- Types sorted in predictable manner -> the CPU can successfully predict the address of the virtual function and this speeds up the computation
- If types are appear randomly , 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

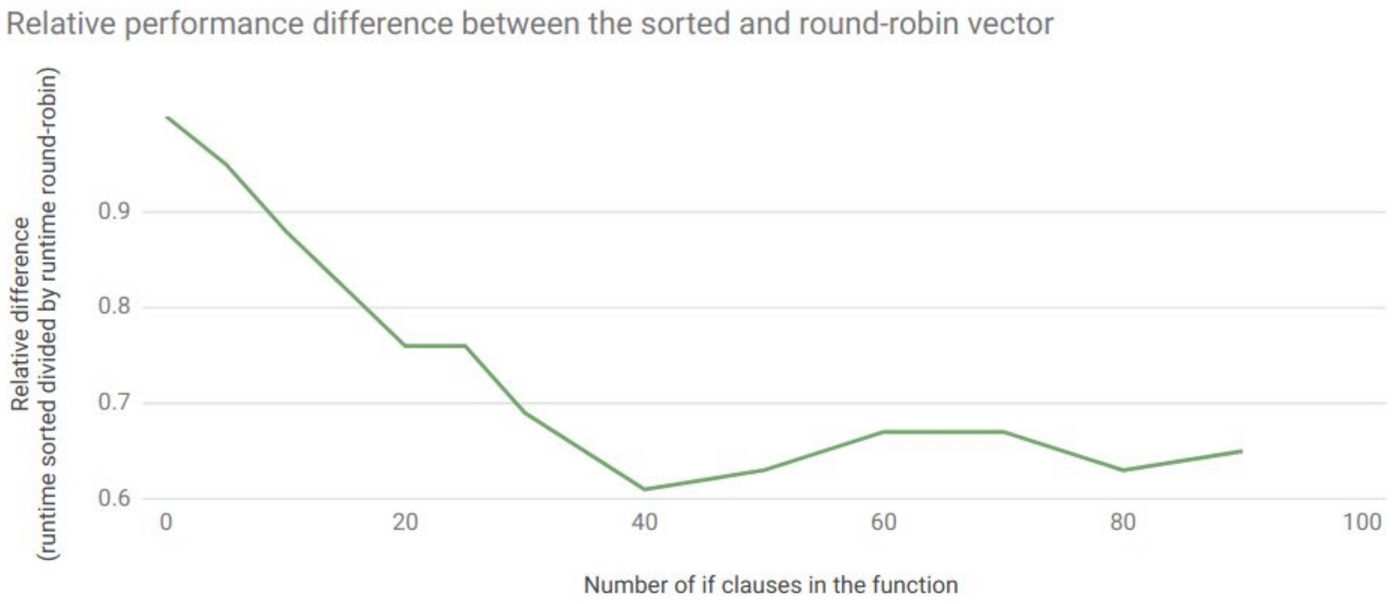
# Instruction Cache Evictions - experiment

- 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
  - E.g, 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
- 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

- Questions?
- Interested in C/C++ software performance? Subscribe:
  - Twitter: @johnysswlab
  - Linkedin: https://www.linkedin.com/company/johnysswlab/
- Need help with performance in your program? Contact us!
  - ivica@johnysswlab.com
  - https://johnysswlab.com/consulting/