STRIVING FOR ULTIMATE LOW LATENCY

INTRODUCTION TO DEVELOPMENT OF LOW LATENCY SYSTEMS

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September 18, 2017

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Especially important for internet connections utilizing services such as trading, online gaming and VoIP.

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- Within capital markets the proliferation of algorithmic trading requires firms to react to market events faster than the competition to increase profitability of trades

HIGH-FREQUENCY TRADING (HFT)

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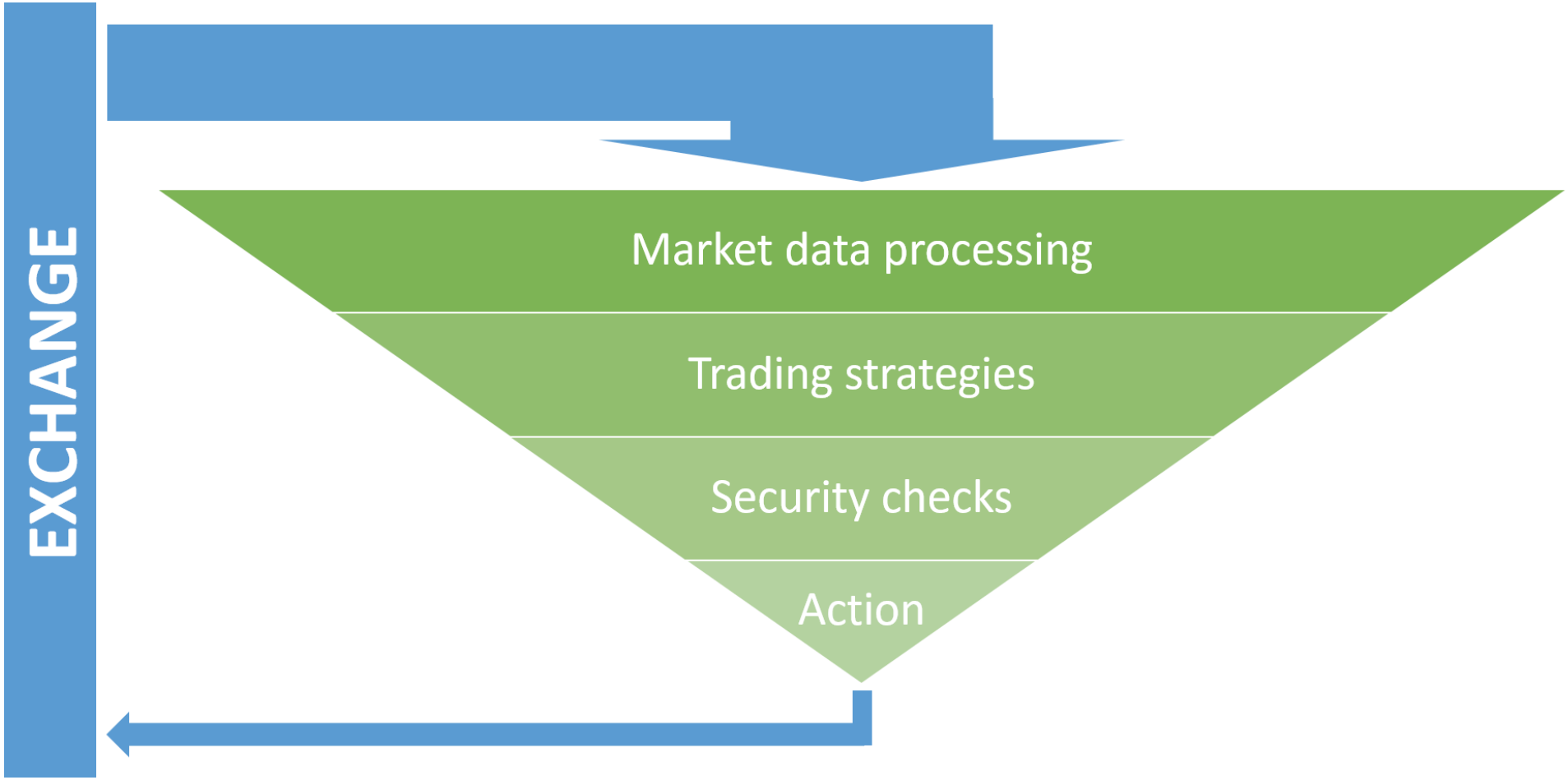
- Using *complex algorithms* to analyze multiple markets and execute orders based on market conditions
- Buying and selling of securities *many times over a period of time* (often hundreds of times an hour)
- Done to *profit from time-sensitive opportunities* that arise during trading hours
- Implies *high turnover of capital* (i.e. one's entire capital or more in a single day)
- Typically, the traders with **the fastest execution speeds** are more profitable

MARKET DATA PROCESSING



HOW FAST DO WE DO?

ALL SOFTWARE APPROACH

1-10us

ALL HARDWARE APPROACH

100-1000ns

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- Average human eye blink takes 350 000us (1/3s)
- Millions of orders can be traded that time

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KNIGHT CAPITAL

- In 2012 was the largest trader in U.S. equities
- Market share
  - 17.3% on NYSE
  - 16.9% on NASDAQ
- Had approximately *$365 million* in cash and equivalents
- Average **daily** trading volume
  - 3.3 billion trades
  - trading over *21 billion* dollars

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  - trading over *21 billion* dollars
- **pre-tax loss of $440 million in 45 minutes**

-- LinkedIn

How a software bug made Knight Capital lose $500M in a day & almost go bankrupt

C++ OFTEN NOT THE MOST IMPORTANT PART OF THE SYSTEM

- Low Latency network
- Modern hardware
- BIOS profiling
- Kernel profiling
- OS profiling

SPIN, PIN, AND DROP-IN

SPIN

- Don't sleep
- Don't context switch
- Prefer single-threaded scheduling
- Disable locking and thread support
- Disable power management
- Disable C-states
- Disable interrupt coalescing

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- Assign interrupt affinity
- Assign memory to NUMA nodes
- Consider the physical location of NICs
- Isolate cores from general OS use
- Use a system with a single physical CPU

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DROP-IN

- Choose NIC vendors based on performance and availability of drop-in kernel bypass libraries
- Use the kernel bypass library

LET'S SCOPE ON THE SOFTWARE

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  - concurrency (even on different cores) trashes CPU caches above L1, share memory bus, shares IO, shares network
- **Mistakes are really costly**
  - good error checking and recovery is mandatory
  - one second is 4 billion CPU instructions (a lot can happen that time)

HOW TO DEVELOP SOFTWARE THAT HAVE PREDICTABLE PERFORMANCE?

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It turns out that the more important question here is...

HOW NOT TO DEVELOP SOFTWARE THAT HAVE PREDICTABLE PERFORMANCE?

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- In Low Latency system we care a lot about WCET (Worst Case Execution Time)
- In order to limit WCET we should limit the usage of specific C++ language features
- This is not only the task for developers but also for code architects

THINGS TO AVOID ON THE FAST PATH

1. C++ tools that trade performance for usability (e.g. `std::shared_ptr<T>`, `std::function<>`)
2. Throwing exceptions on likely code path
3. Dynamic polymorphism
4. Multiple inheritance
5. RTTI
6. Dynamic memory allocations

std::shared_ptr<T>

```
template<class T>
class shared_ptr;
```

- Smart pointer that retains **shared ownership** of an object through a pointer
- Several **`shared_ptr`** objects **may own the same object**
- The shared object is destroyed and its memory deallocated when the last remaining **`shared_ptr`** owning that object is either destroyed or assigned another pointer via **`operator=`** or **`reset()`**
- Support user provided **deleter**

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Too often overused by C++ programmers

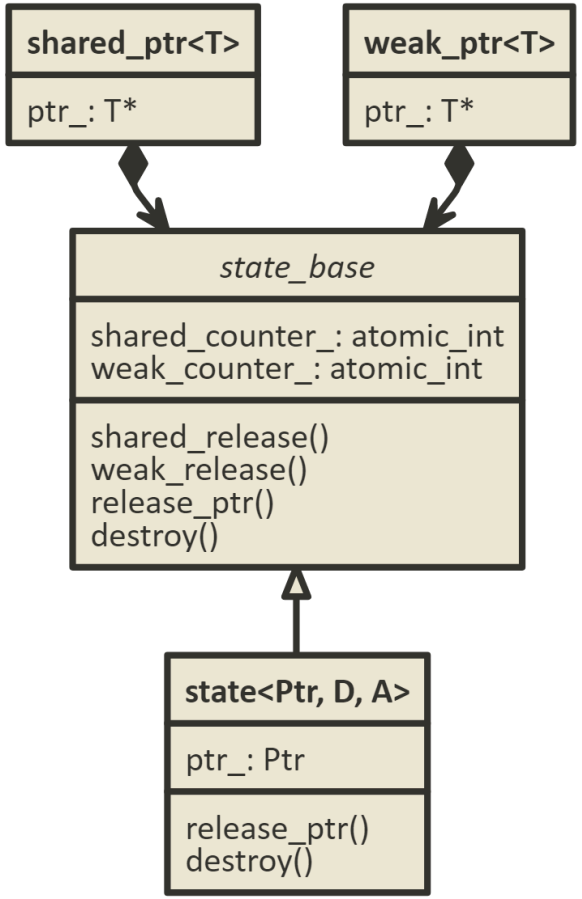
QUESTION: WHAT IS THE DIFFERENCE HERE?

```
void foo()
{
  std::unique_ptr<int> ptr{new int{1}};
  // some code using 'ptr'
}
```

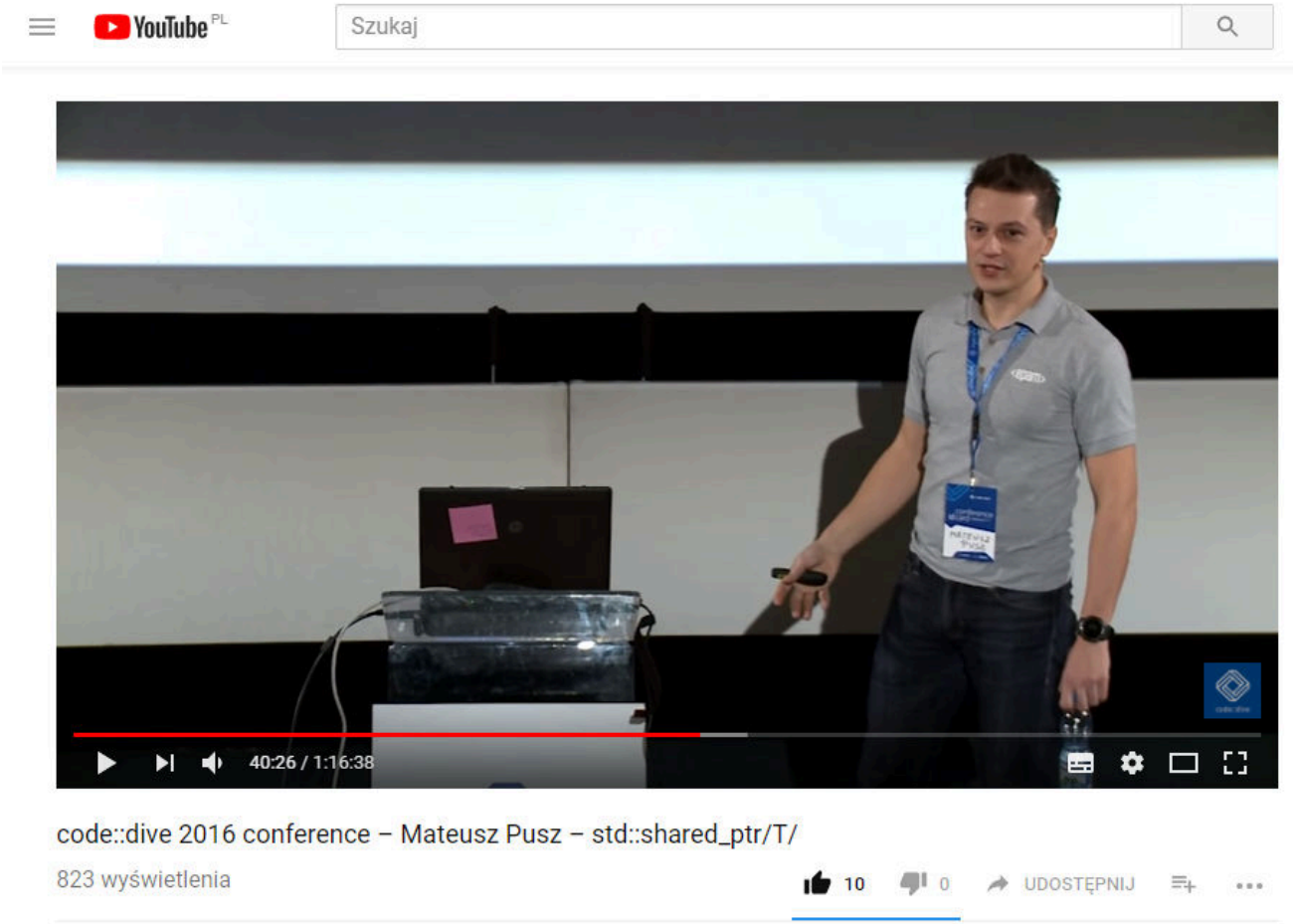
```
void foo()
{
  std::shared_ptr<int> ptr{new int{1}};
  // some code using 'ptr'
}
```

KEY `std::shared_ptr<T>` ISSUES

- Shared state
  - performance + memory footprint
- Mandatory synchronization
  - performance
- Type Erasure
  - performance
- `std::weak_ptr<T>` support
  - memory footprint
- Aliasing constructor
  - memory footprint



MORE INFO ON CODE::DIVE 2016



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Not using C++ exceptions is not an excuse to write not exception-safe code!

POLYMORPHISM

DYNAMIC

```
class base {
  virtual void setup() = 0;
  virtual void run() = 0;
  virtual void cleanup() = 0;
public:
  virtual ~base() = default;
  void process()
  {
    setup();
    run();
    cleanup();
  }
};

class derived : public base {
  void setup() override   { /* ... */ }
  void run() override     { /* ... */ }
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- Additional pointer stored in an object
- Extra indirection (pointer dereference)
- Often not possible to devirtualize
- Not inlined
- Instruction cache miss

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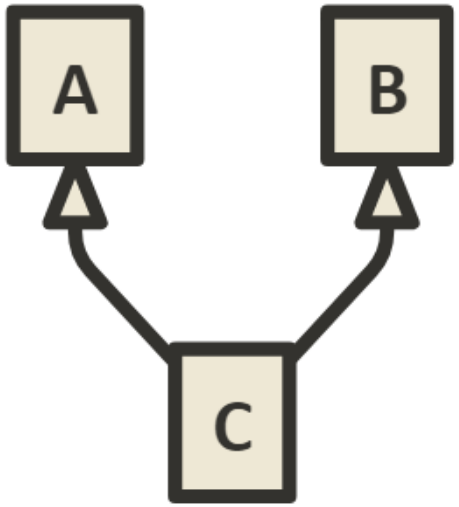
STATIC

```
template<class Derived>
class base {
public:
  void process()
  {
    static_cast<Derived*>(this)->setup();
    static_cast<Derived*>(this)->run();
    static_cast<Derived*>(this)->cleanup();
  }
};

class derived : public base<derived> {
  friend class base<derived>;
  void setup()   { /* ... */ }
  void run()     { /* ... */ }
  void cleanup() { /* ... */ }
};
```

MULTIPLE INHERITANCE



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- **`this`** pointer adjustments needed to call member function (for not empty base classes)

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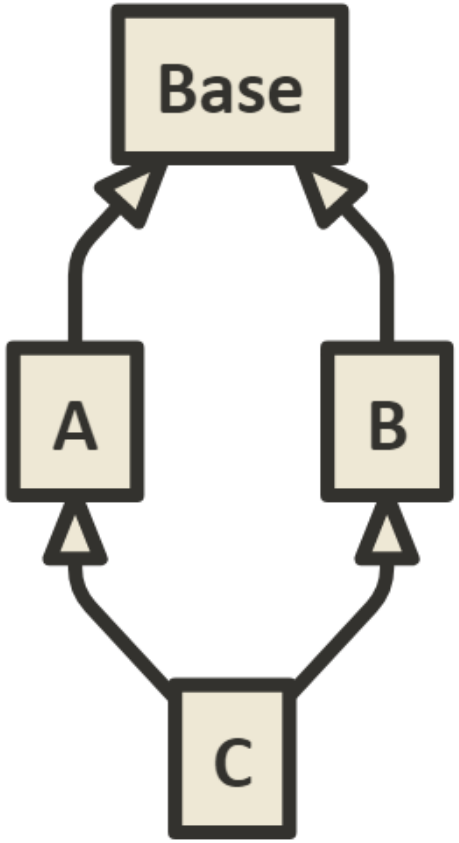

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- Virtual inheritance as an answer
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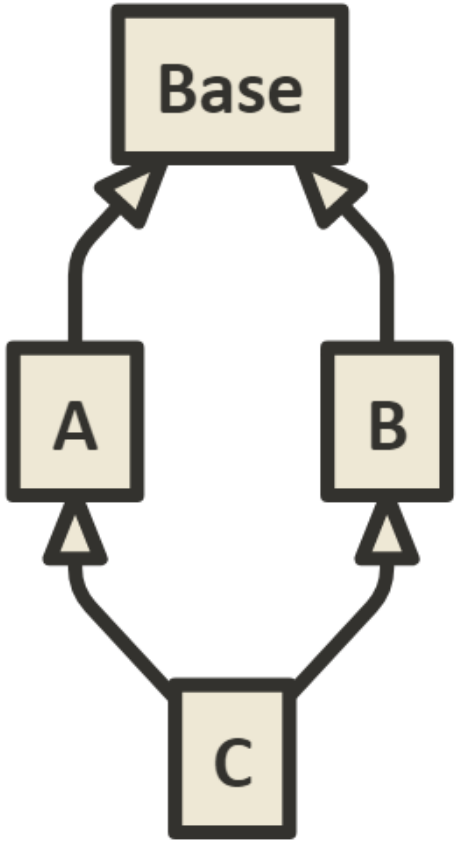

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Always consider composition before inheritance!

RUNTIME TYPE IDENTIFICATION (RTTI)

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```
class derived : public base {
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```
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  derived* d = dynamic_cast<derived*>(&b);
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Often the sign of a *smelly* design

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  if(typeid(b) == typeid(derived)) {
    derived* d = static_cast<derived*>(&b);
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}
```

- Traversing an inheritance tree
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- Only one comparison of **`std::type_info`**
- Often only one runtime pointer compare

DYNAMIC MEMORY ALLOCATIONS

- *General purpose* operation
- *Nondeterministic* execution performance
- Causes memory *fragmentation*
- *Memory leaks* possible if not properly handled
- May *fail* (error handling is needed)

CUSTOM ALLOCATORS TO THE RESCUE

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template<typename T> struct pool_allocator {
  T* allocate(std::size_t n);
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using pool_string = std::basic_string<char, std::char_traits<char>, pool_allocator>;
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Preallocation makes the allocator *jitter more stable*, helps in keeping *related data together* and avoiding long term *fragmentation*.

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Prevent dynamic memory allocation for the (common) case of dealing with small objects

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```
class sso_string {
  char* data_ = u_.sso_;
  size_t size_ = 0;
  union {
    char sso_[16] = "";
    size_t capacity_;
  } u_;
public:
  size_t capacity() const { return data_ == u_.sso_ ? sizeof(u_.sso_) - 1 : u_.capacity_; }
  // ...
};
```

NO DYNAMIC ALLOCATION

```
template<std::size_t MaxSize>
class inplace_string {
  std::array<value_type, MaxSize + 1> chars_;
public:
  // string-like interface
};
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```
struct db_contact {
  inplace_string<7> symbol;
  inplace_string<15> name;
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};
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No dynamic memory allocations or pointer indirections guaranteed with the cost of possibly bigger memory usage

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- **Measure** performance… **ALWAYS**

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Always measure your performance!

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- Always measure **Release** version

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- Prefer *hardware based black box* performance meassurements
- In case that is not possible or you want to debug specific performance issue use *profiler*
- To gather meaningful stack traces *preserve frame pointer*

```
set(CMAKE_CXX_FLAGS_RELWITHDEBINFO
    "${CMAKE_CXX_FLAGS_RELWITHDEBINFO} -fno-omit-frame-pointer")
```

- Familiarize yourself with linux perf tools (xperf on Windows) and flame graphs
- Use tools like Intel VTune

HOW TO MEASURE THE PERFORMANCE OF YOUR PROGRAMS

- Always measure **Release** version

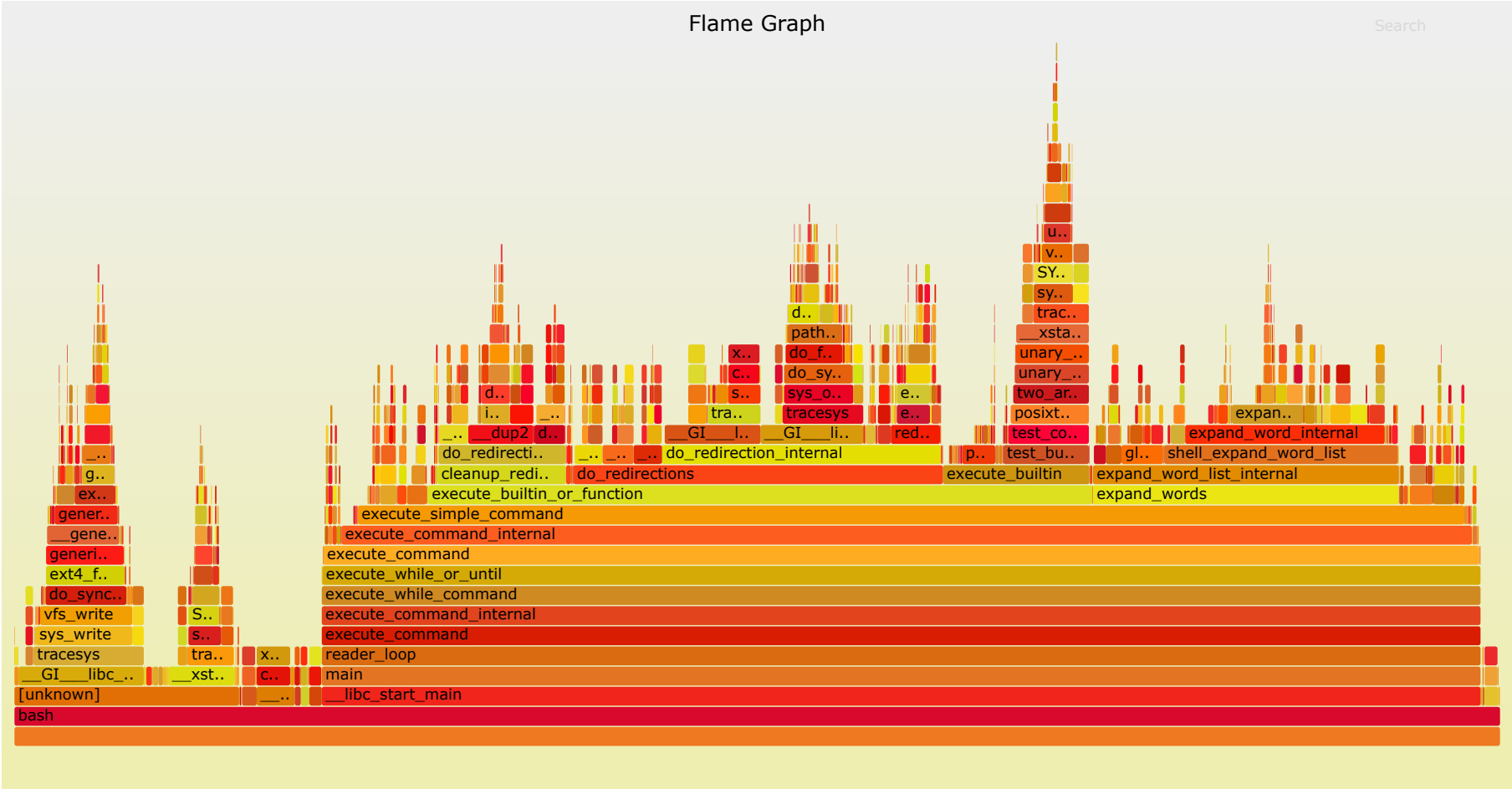
```
cmake -DCMAKE_BUILD_TYPE=Release
cmake -DCMAKE_BUILD_TYPE=RelWithDebInfo
```

- Prefer *hardware based black box* performance meassurements
- In case that is not possible or you want to debug specific performance issue use *profiler*
- To gather meaningful stack traces *preserve frame pointer*

```
set(CMAKE_CXX_FLAGS_RELWITHDEBINFO
    "${CMAKE_CXX_FLAGS_RELWITHDEBINFO} -fno-omit-frame-pointer")
```

- Familiarize yourself with linux perf tools (xperf on Windows) and flame graphs
- Use tools like Intel VTune
- *Verify output assembly code*

FLAMEGRAPH


Flame Graph
Search
u..
v..
SY..
sy..
trac..
__xsta..
unary_..
unary_..
two_ar..
posixt..
test_co..
test_bu..
expan..
expand_word_internal
gl..
shell_expand_word_list
expand_word_list_internal
expand_words
execute_builtin
p..
d..
path..
do_f..
do_sy..
sys_o..
tracesys
e..
e..
red..
x..
c..
s..
tra..
__GI____l..
__GI____li..
d..
i..
_..
__dup2
d..
do_redirecti..
do_redirection_internal
do_redirections
cleanup_redi..
execute_builtin_or_function
execute_simple_command
execute_command_internal
execute_command
execute_while_or_until
execute_while_command
execute_command_internal
execute_command
reader_loop
main
__libc_start_main
g..
ex..
gener..
__gene..
generi..
ext4_f..
do_sync..
vfs_write
sys_write
tracesys
__GI____libc_..
[unknown]
bash
S..
s..
tra..
__xst..
x..
c..
__..

CAUTION
Programming
is addictive
(and too much fun)