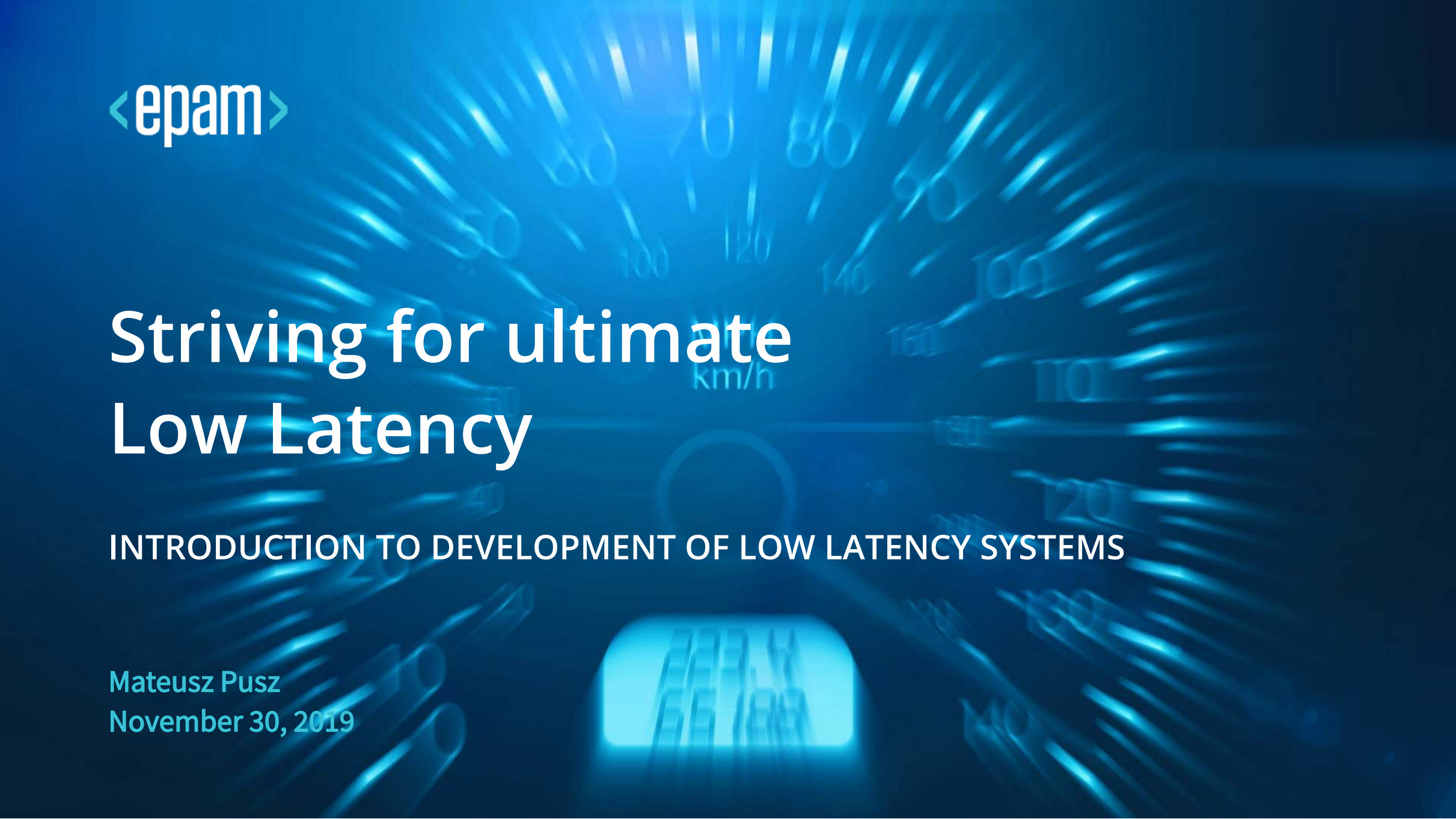

Striving for ultimate Low Latency

INTRODUCTION TO DEVELOPMENT OF LOW LATENCY SYSTEMS

Mateusz Pusz
November 30, 2019

ISO C++ Committee (WG21) Study Group 14 (SG14)

Special thanks to Carl Cook and Chris Kohlhoff

Latency vs Throughput

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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)

A program trading platform that uses powerful computers to transact a large number of orders at very fast speeds

-- Investopedia

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- Typically, the traders with **the fastest execution speeds** are more profitable

Market data processing

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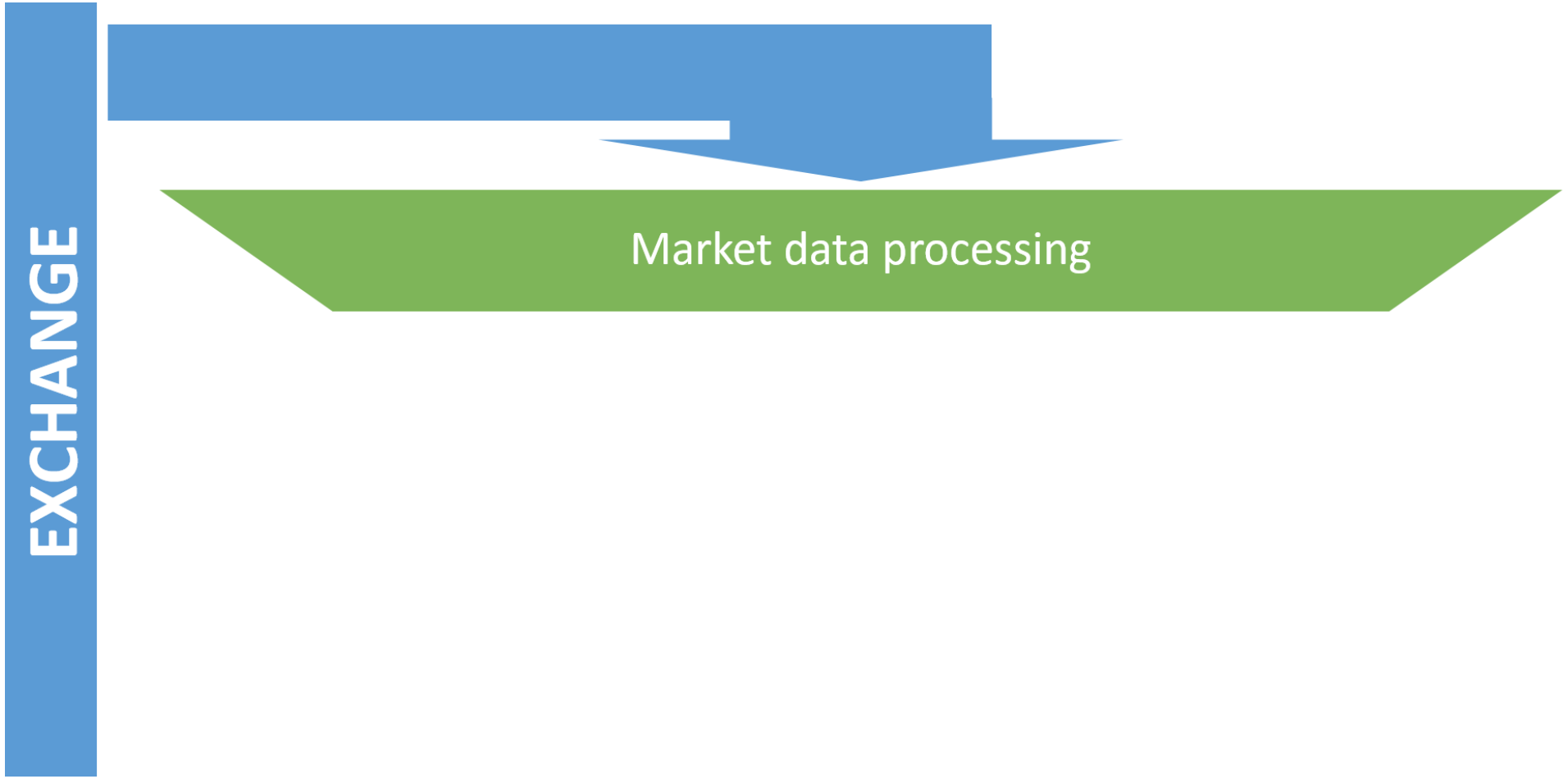

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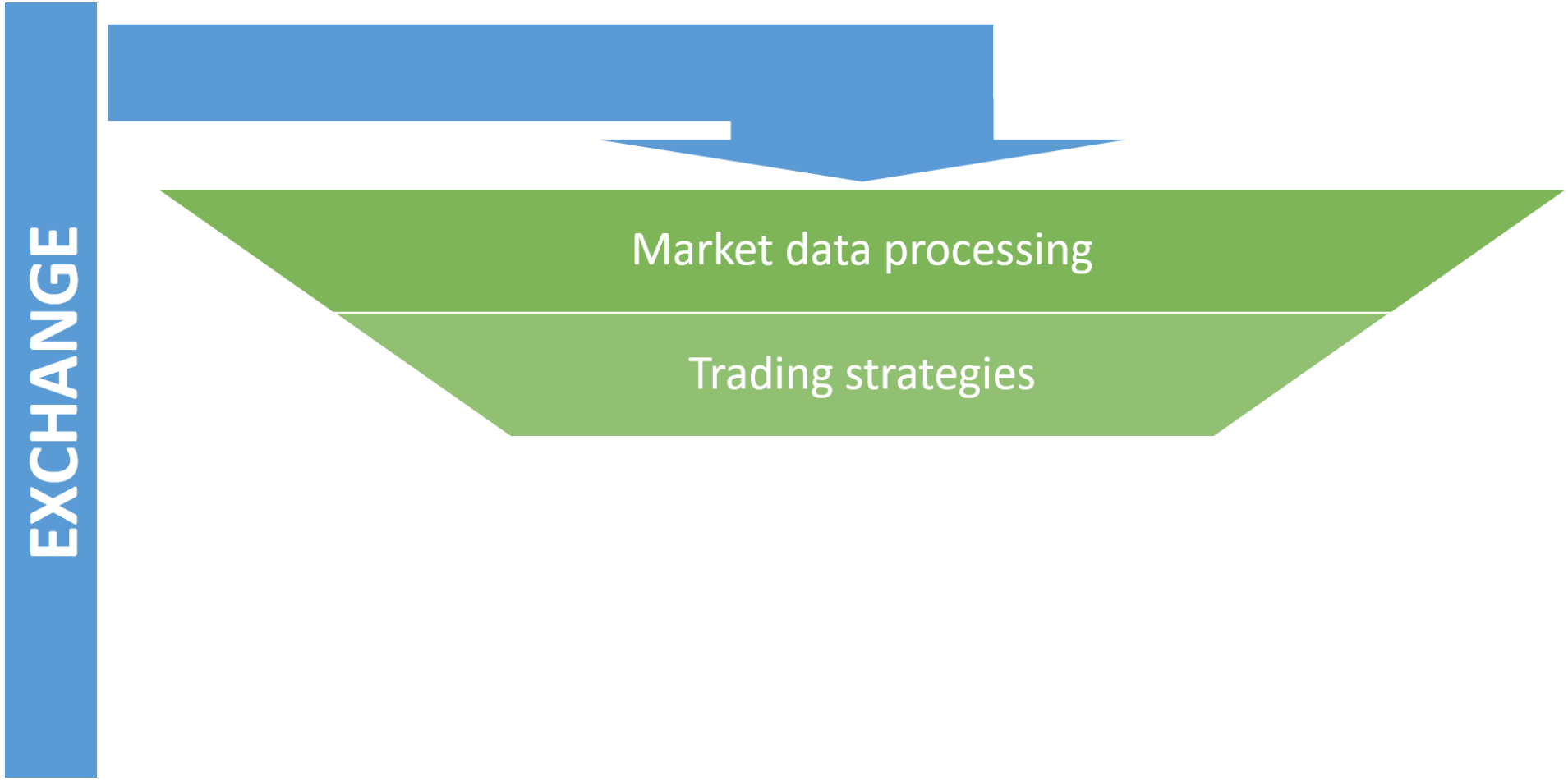

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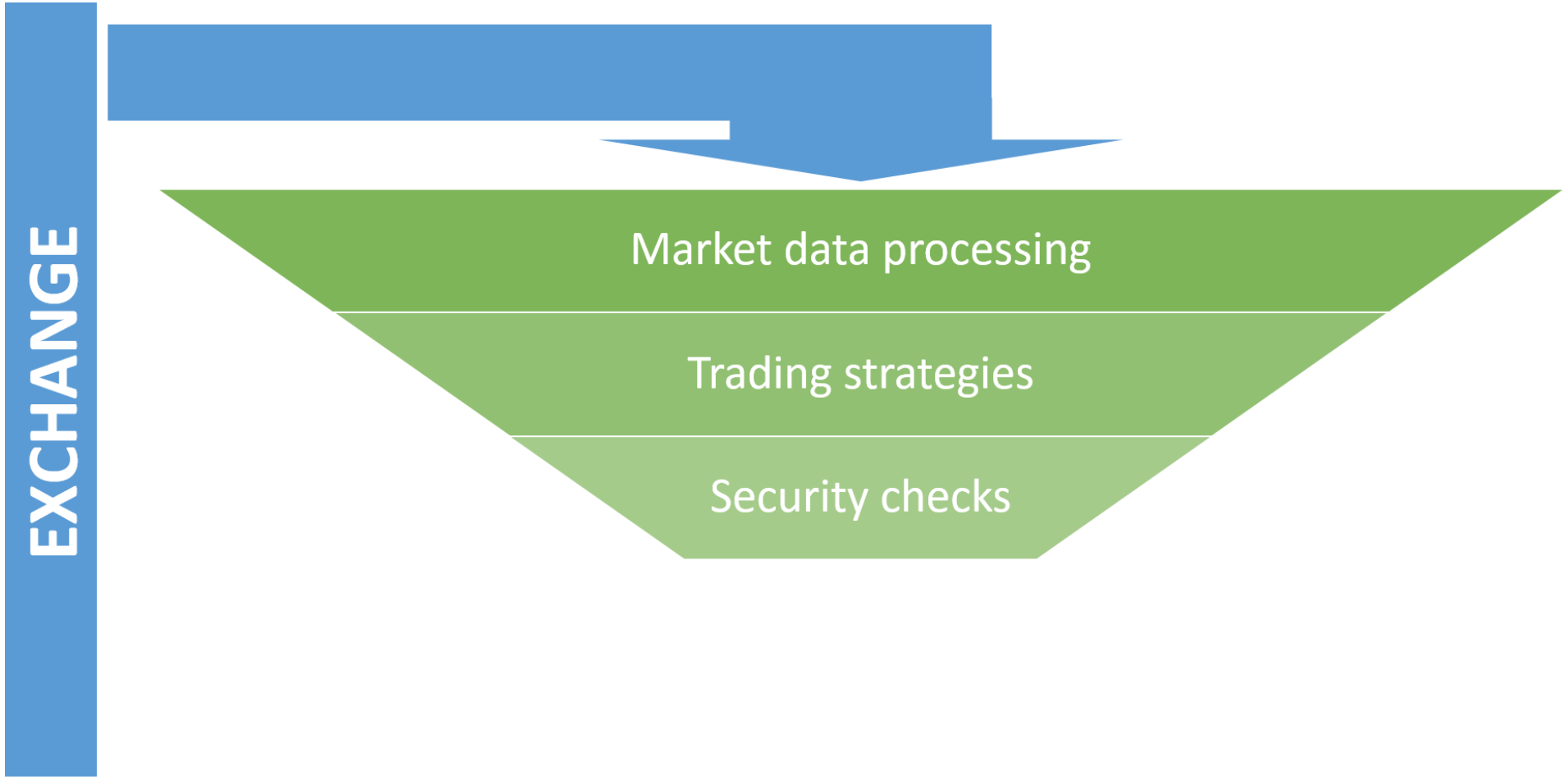

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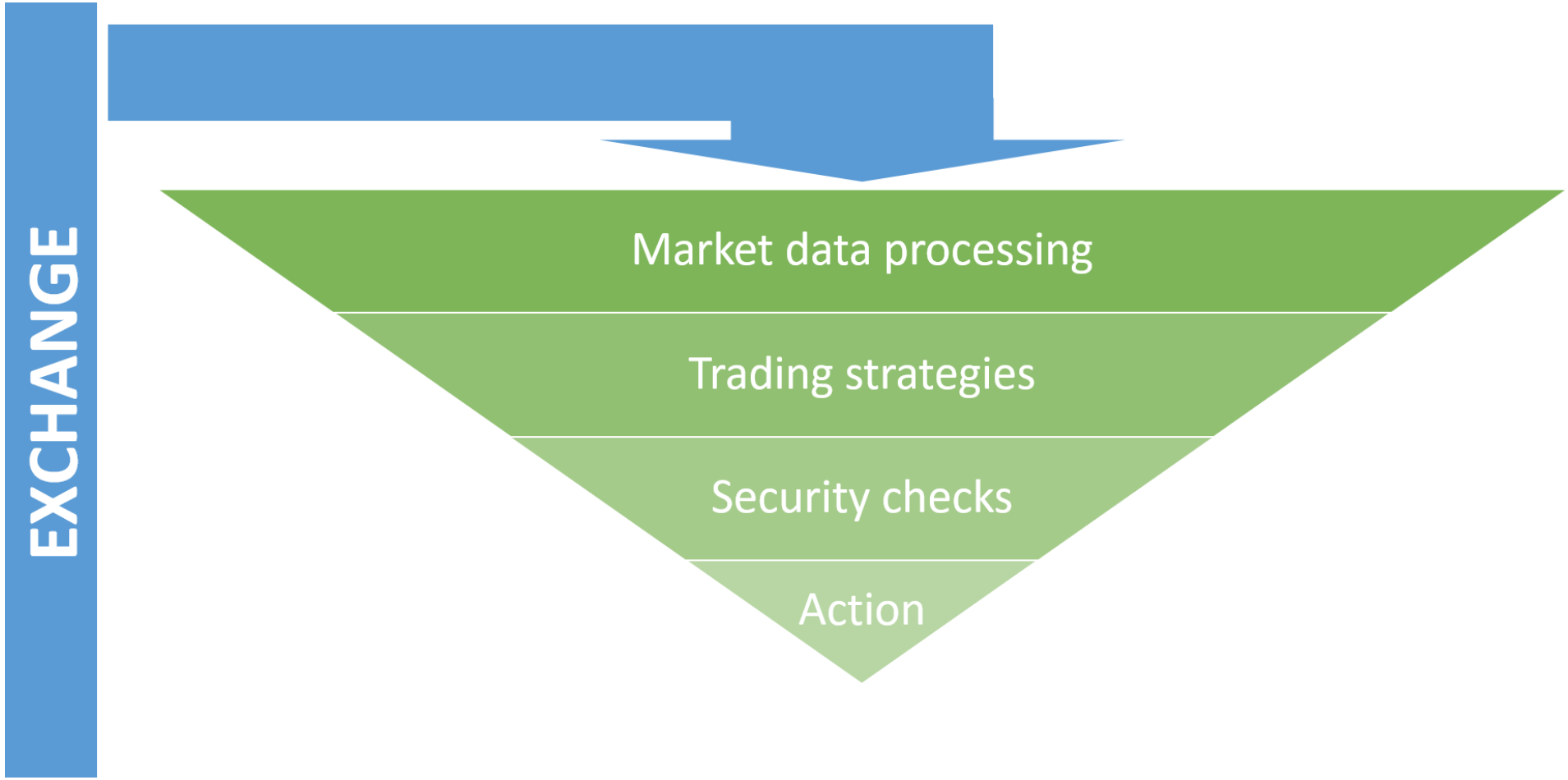

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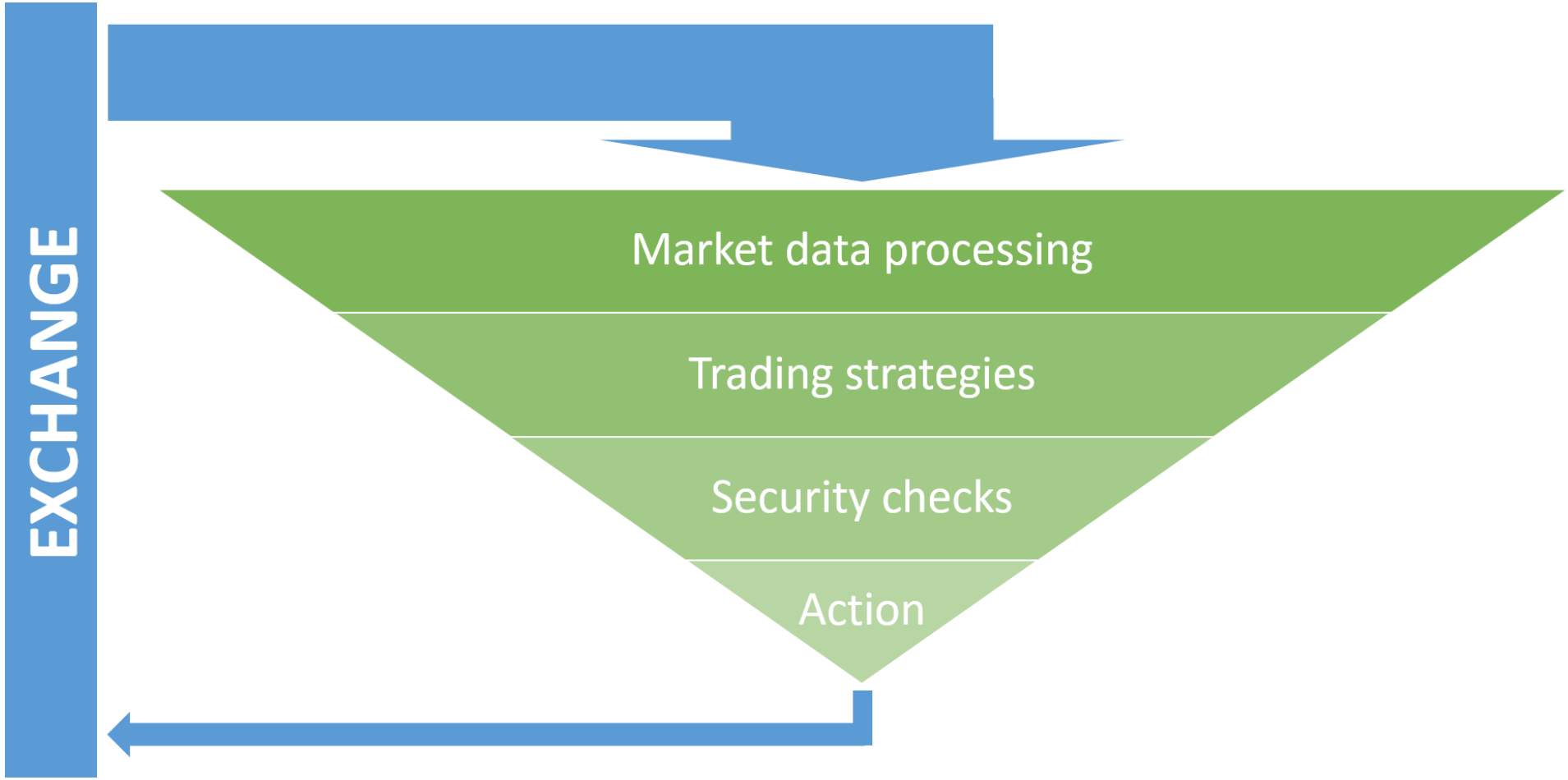

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1-10us

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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- **pre-tax loss of $440 million in 45 minutes**

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

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Spin, pin, and drop-in

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- Don't sleep
- Don't context switch
- Prefer single-threaded scheduling
- Disable locking and thread support
- Disable power management
- Disable C-states
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- Assign interrupt affinity
- Assign memory to NUMA nodes
- Consider the physical location of NICs
- Isolate cores from general OS use
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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 expensive**
  - 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

How NOT to develop software that have predictable performance?

- 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
- A task not only for developers but also for code architects

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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()**
- Supports user provided deleter

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- Supports user provided **deleter**

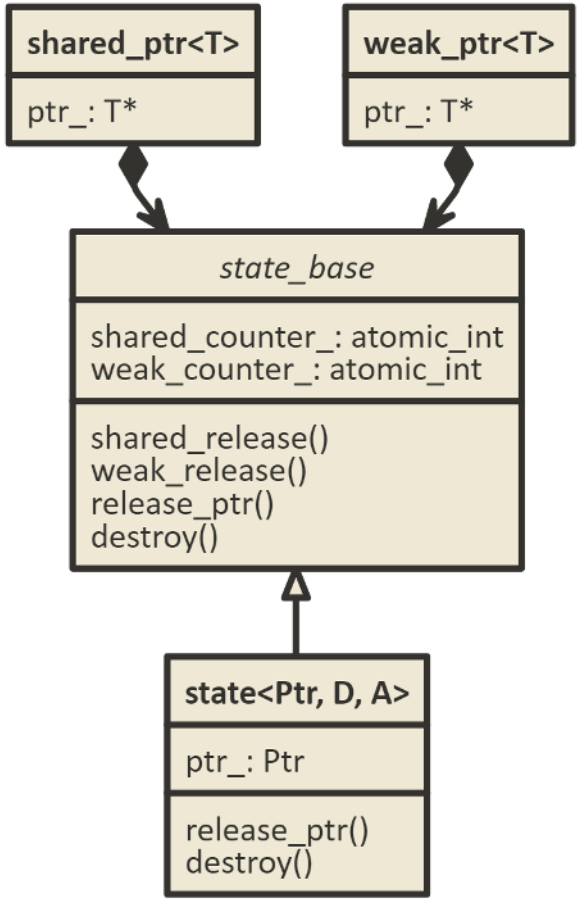
Too often overused by C++ programmers

Question: What is the difference here?

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

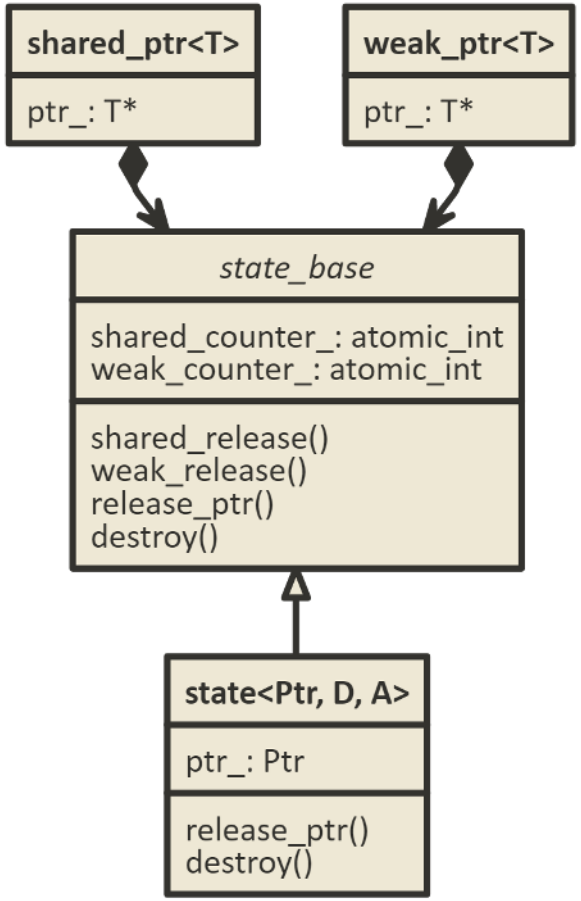
```cpp
void foo()
{
  std::shared_ptr<int> ptr{new int{1}};
  // some code using 'ptr'
}
```

Key `std::shared_ptr<T>` issues

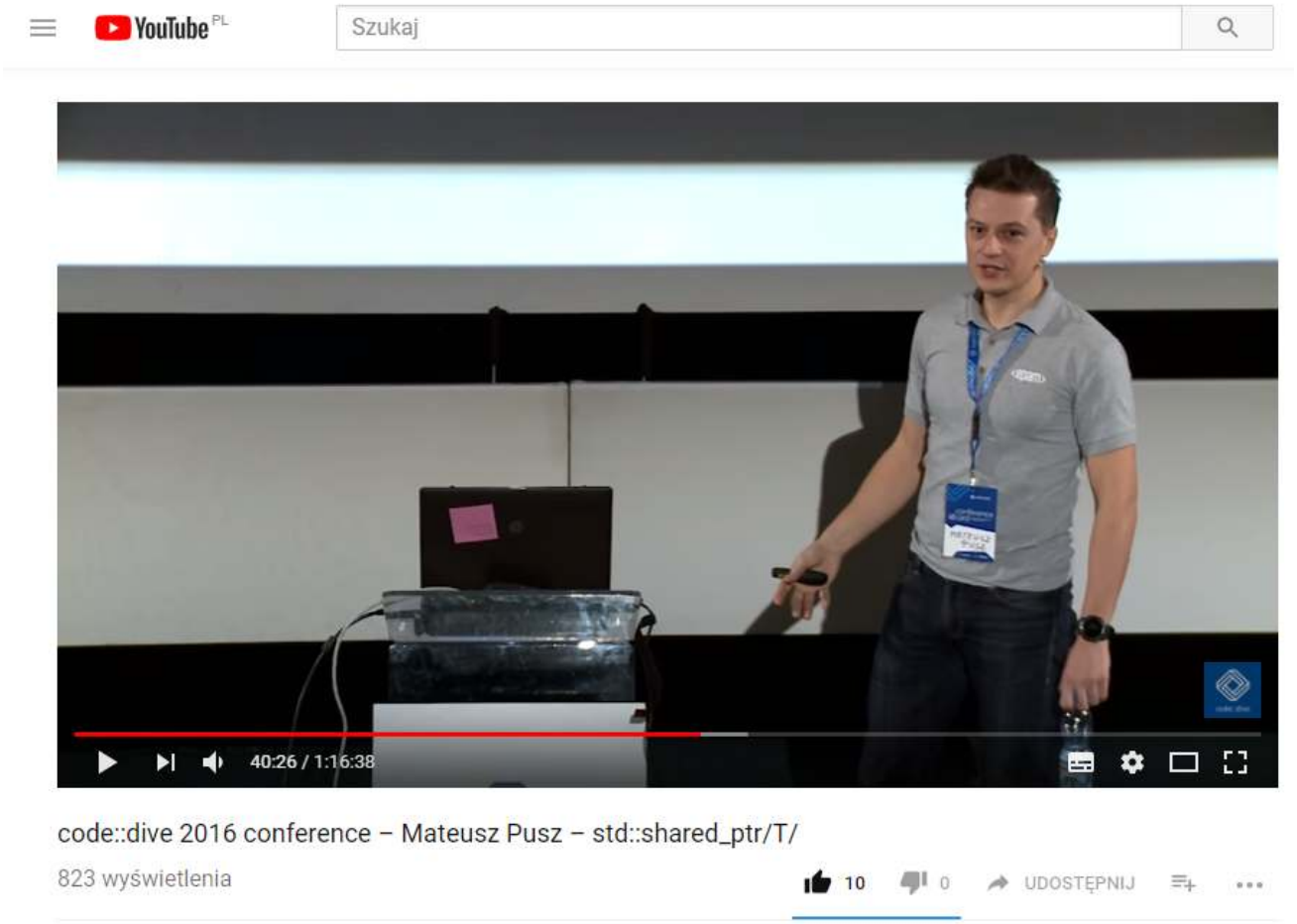


Key `std::shared_ptr<T>` issues

- 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

Polymorphism

DYNAMIC

```
class base : noncopyable {
  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()   { /* ... */ }
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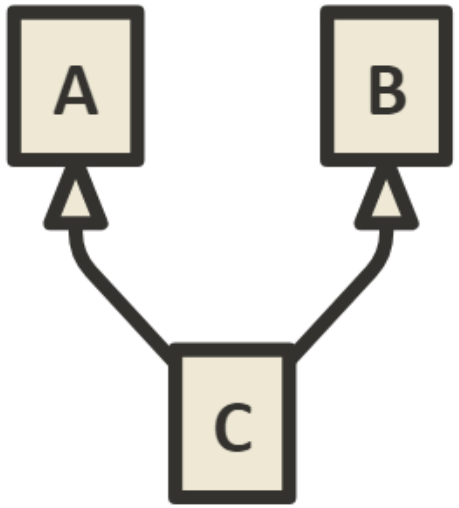
};
```

Multiple inheritance



MULTIPLE INHERITANCE

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

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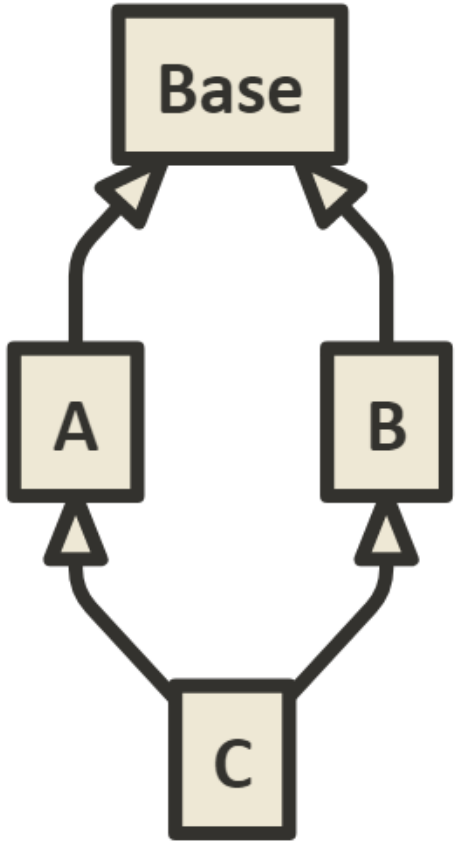

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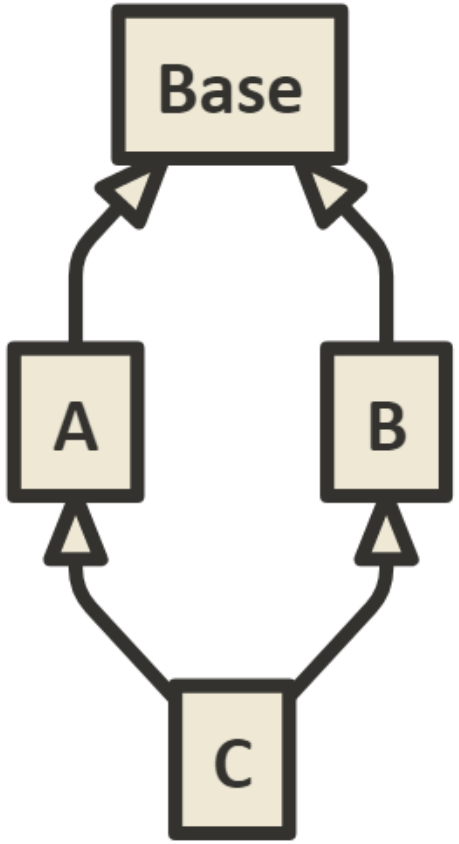

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Always prefer composition before inheritance!

RunTime Type Identification (RTTI)

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class base : noncopyable {
public:
  virtual ~base() = default;
  virtual void foo() = 0;
};
```

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

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- Comparisons

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- Traversing an inheritance tree
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```
void foo(base& b)
{
  if(typeid(b) == typeid(derived)) {
    derived* d = static_cast<derived*>(&b);
    d->boo();
  }
}
```

- 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*
- May *fail* (error handling is needed)
- *Memory leaks* possible if not properly handled

Custom allocators to the rescue

- Address *specific needs* (functionality and hardware constrains)
- Typically *low number of* dynamic memory *allocations*
- *Data structures* needed to manage big chunks of memory

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  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*.

Small Object Optimization (SOO / SSO / SBO)

- *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:
  [[nodiscard]] 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;
  inplace_string<15> surname;
  inplace_string<23> company;
};
```

No dynamic allocation

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```

```cpp
struct db_contact {
  inplace_string<7> symbol;
  inplace_string<15> name;
  inplace_string<15> surname;
  inplace_string<23> company;
};
```

No dynamic memory allocations or pointer indirections guaranteed with the cost of possibly bigger memory usage

The list of things to do on the fast path

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1. Use tools that **improve efficiency without sacrificing performance**

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1. Use tools that **improve efficiency without sacrificing performance**
2. Use **compile time** wherever possible

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3. **Know your hardware**

The list of things to do on the fast path

1. Use tools that **improve efficiency without sacrificing performance**
2. Use **compile time** wherever possible
3. **Know your hardware**
4. Clearly **isolate cold code from the fast path**

Examples of safe to use C++ features

- **`static_assert()`**
- Automatic type deduction
- Type aliases
- Move semantics
- **`noexcept`**
- **`constexpr`**
- Lambda expressions
- **`type_traits`**
- **`std::string_view`**
- Variadic templates
- and many more...

Do you agree?

The fastest programs are those that do nothing

Compile-time calculations (C++98)

```
int factorial(int n)
{
  int result = n;
  while(n > 1)
    result *= --n;
  return result;
}
```

```
foo(factorial(n));  // not compile-time
foo(factorial(4));  // not compile-time
```

Compile-time calculations (C++98)

```
int factorial(int n)
{
  int result = n;
  while(n > 1)
    result *= --n;
  return result;
}
```

```
foo(factorial(n));  // not compile-time
foo(factorial(4));  // not compile-time
```

```
template<int N>
struct Factorial {
  static const int value =
      N * Factorial<N - 1>::value;
};

template<>
struct Factorial<0> {
  static const int value = 1;
};
```

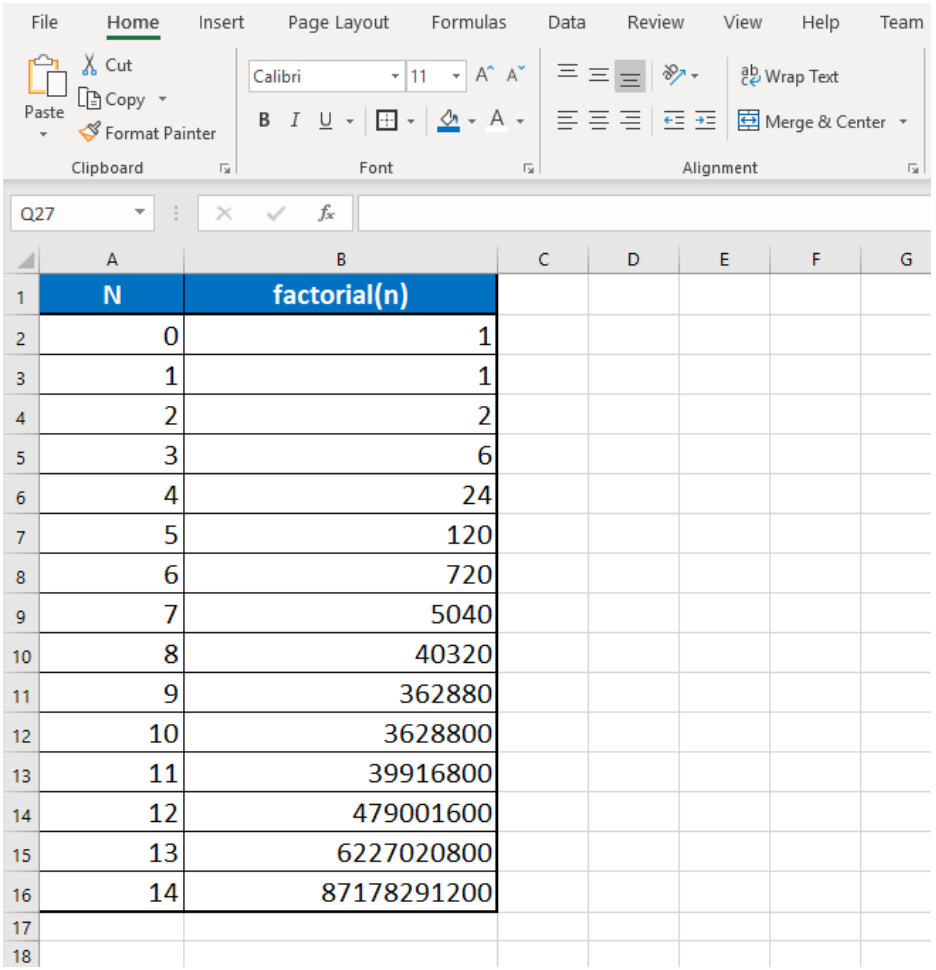
```
int array[Factorial<4>::value];
```

```
const int precalc_values[] = {
  Factorial<0>::value,
  Factorial<1>::value,
  Factorial<2>::value
};
```

```
foo(factorial<4>::value);  // compile-time
// foo(factorial<n>::value);  // compile-time error
```

Just too hard!

- 2 separate implementations
  - hard to keep in sync
- Template *metaprogramming* is hard!
- Easier to precalculate in Excel and hardcode results in the code ;-)

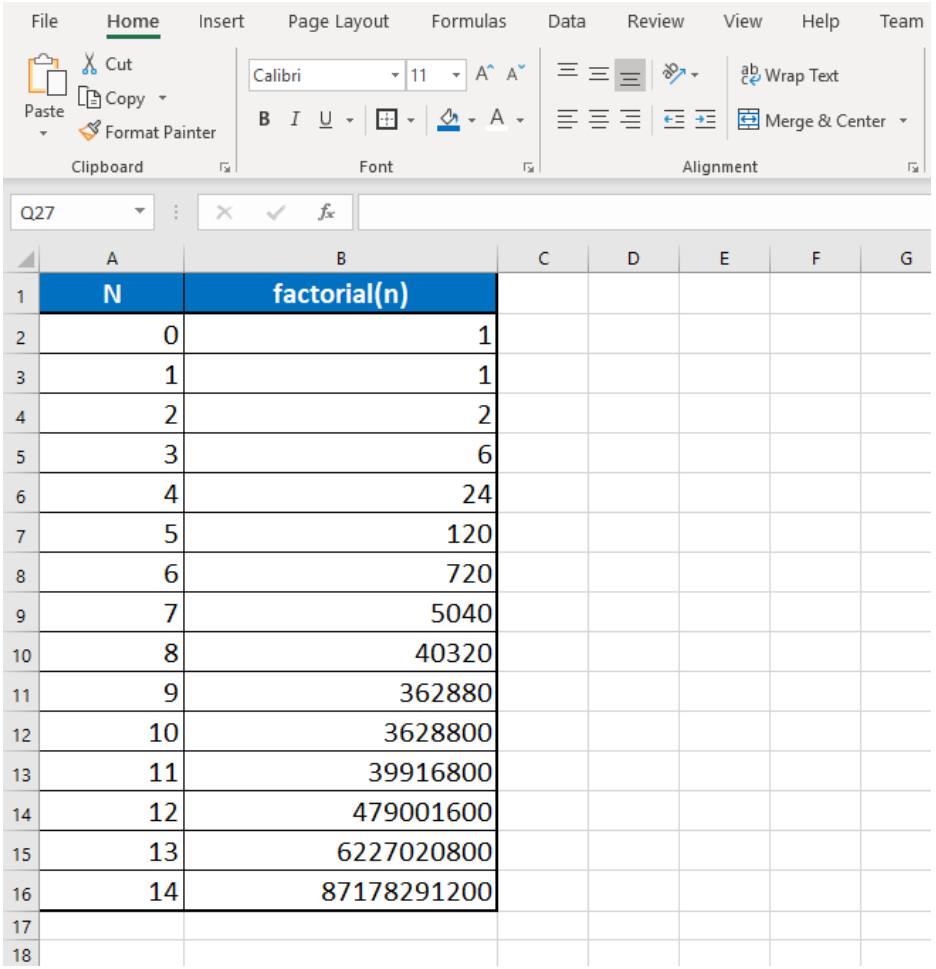


	A	B	C	D	E	F	G
1	N	factorial(n)					
2	0	1					
3	1	1					
4	2	2					
5	3	6					
6	4	24					
7	5	120					
8	6	720					
9	7	5040					
10	8	40320					
11	9	362880					
12	10	3628800					
13	11	39916800					
14	12	479001600					
15	13	6227020800					
16	14	87178291200					
17							
18							

Just too hard!

- 2 separate implementations
  - hard to keep in sync
- Template *metaprogramming* is hard!
- Easier to precalculate in Excel and hardcode results in the code ;-)

```
const int precalc_values[] = {
  1,
  1,
  2,
  6,
  24,
  120,
  720,
  // ...
};
```



	A	B	C	D	E	F	G
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17							
18							

`constexpr` specifier

Declares that it is **possible to evaluate** the value of the function or variable **at compile time**

`constexpr` specifier

Declares that it is **possible to evaluate** the value of the function or variable **at compile time**

- **`constexpr`** specifier used in an *object declaration implies* ***`const`***
- **`constexpr`** specifier used in a *function* or *static member variable declaration implies* ***`inline`***

`constexpr` specifier

Declares that it is **possible to evaluate** the value of the function or variable **at compile time**

- **`constexpr`** specifier used in an *object declaration implies* ***`const`***
- **`constexpr`** specifier used in a *function* or *static member variable declaration implies* ***`inline`***
- Such variables and functions *can be used in compile time constant expressions* (provided that appropriate function arguments are given)

```
constexpr int factorial(int n);
```

```
std::array<int, factorial(4)> array;
```

Compile-time calculations (C++11)

- A **constexpr** function must not be virtual
- The function body may contain only
  - **static_assert** declarations
  - alias declarations
  - using declarations and directives
  - exactly one return statement with an expression that does not mutate any of the objects

```
constexpr int factorial(int n)
{
  return n <= 1 ? 1 : (n * factorial(n - 1));
}
```

```
std::array<int, factorial(4)> array;
```

```
constexpr std::array<int, 3> precalc_values = {
  factorial(0),
  factorial(1),
  factorial(2)
};
```

```
static_assert(factorial(4) == 24, "Error");
foo(factorial(4));  // maybe compile-time
foo(factorial(n));  // not compile-time
```

Compile-time calculations (C++14)

- A **constexpr** function must not be virtual
- The function body must not contain
  - a **goto** statement and labels other than **case** and **default**
  - a **try** block
  - an **asm** declaration
  - variable of *non-literal type*
  - variable of *static* or *thread storage duration*
  - *uninitialized* variable
  - evaluation of a *lambda expression*
  - **reinterpret_cast** and **dynamic_cast**
  - *changing an active member* of an union
  - a **new** or **delete** expression

```
constexpr int factorial(int n)
{
  int result = n;
  while(n > 1)
    result *= --n;
  return result;
}
```

```
std::array<int, factorial(4)> array;
```

```
constexpr std::array<int, 3> precalc_values = {
  factorial(0),
  factorial(1),
  factorial(2)
};
```

```
static_assert(factorial(4) == 24, "Error");
foo(factorial(4));  // maybe compile-time
foo(factorial(n));  // not compile-time
```

Compile-time calculations (C++17)

- A **constexpr** function must not be virtual
- The function body must not contain
  - a **goto** statement and labels other than **case** and **default**
  - a **try** block
  - an **asm** declaration
  - variable of *non-literal type*
  - variable of *static* or *thread storage duration*
  - *uninitialized* variable
  - **reinterpret_cast** and **dynamic_cast**
  - *changing an active member* of an union
  - a **new** or **delete** expression

```
constexpr int factorial(int n)
{
  int result = n;
  while(n > 1)
    result *= --n;
  return result;
}
```

```
std::array<int, factorial(4)> array;
```

```
constexpr std::array precalc_values = {
  factorial(0),
  factorial(1),
  factorial(2)
};
```

```
static_assert(factorial(4) == 24);
foo(factorial(4));  // maybe compile-time
foo(factorial(n));  // not compile-time
```

Compile-time calculations (C++20)

- The function body **must not contain**
  - a **goto** statement and labels other than **case** and **default**
  - variable of *non-literal type*
  - variable of *static* or *thread storage duration*
  - *uninitialized* variable
  - **reinterpret_cast**

```
constexpr int factorial(int n)
{
  int result = n;
  while(n > 1)
    result *= --n;
  return result;
}
```

```
std::array<int, factorial(4)> array;
```

```
constexpr std::array precalc_values = {
  factorial(0),
  factorial(1),
  factorial(2)
};
```

```
static_assert(factorial(4) == 24);
foo(factorial(4));  // maybe compile-time
foo(factorial(n));  // not compile-time
```

Compile-time calculations (C++20)

- The **`consteval`** specifier declares a function to be an immediate function
- Every call must produce a compile time constant expression
- An immediate function *is a* ***`constexpr`*** *function*

```
consteval int factorial(int n)
{
  int result = n;
  while(n > 1)
    result *= --n;
  return result;
}
```

```
std::array<int, factorial(4)> array;
```

```
constexpr std::array precalc_values = {
  factorial(0),
  factorial(1),
  factorial(2)
};
```

```
static_assert(factorial(4) == 24);
foo(factorial(4));  // compile-time
// foo(factorial(n));  // compile-time error
```

Compile-time dispatch (C++14)

```cpp
template<typename T>
struct is_array : std::false_type {};

template<typename T>
struct is_array<T[]> : std::true_type {};

template<typename T>
constexpr bool is_array_v = is_array<T>::value;

static_assert(is_array_v<int> == false);
static_assert(is_array_v<int[]>);
```

Compile-time dispatch (C++14)

```cpp
template<typename T>
struct is_array : std::false_type {};

template<typename T>
struct is_array<T[]> : std::true_type {};

template<typename T>
constexpr bool is_array_v = is_array<T>::value;

static_assert(is_array_v<int> == false);
static_assert(is_array_v<int[]>);
```

```cpp
template<typename T>
class smart_ptr {
  void destroy(std::true_type) noexcept
  { delete[] ptr_; }

  void destroy(std::false_type) noexcept
  { delete ptr_; }

  void destroy() noexcept
  { destroy(is_array<T>()); }

  // ...
};
```

Tag dispatch provides the possibility to select the proper function overload in compile-time based on properties of a type

Compile-time dispatch (C++17)

```
template<typename T>
inline constexpr bool is_array = false;

template<typename T>
inline constexpr bool is_array<T[]> = true;

static_assert(is_array<int> == false);
static_assert(is_array<int[]>);
```

Compile-time dispatch (C++17)

```cpp
template<typename T>
inline constexpr bool is_array = false;

template<typename T>
inline constexpr bool is_array<T[]> = true;

static_assert(is_array<int> == false);
static_assert(is_array<int[]>);
```

```cpp
template<typename T>
class smart_ptr {
  void destroy() noexcept
  {
    if constexpr(is_array<T>)
      delete[] ptr_;
    else
      delete ptr_;
  }

  // ...
};
```

Usage of variable templates and **`if constexpr`** decrease compilation time

Type traits: A negative overhead abstraction

```
struct X {
  int a, b, c;
  int id;
};
```

```
void foo(const std::vector<X>& a1, std::vector<X>& a2)
{
  memcpy(a2.data(), a1.data(), a1.size() * sizeof(X));
}
```

Type traits: A negative overhead abstraction

```
struct X {
  int a, b, c;
  int id;
};
```

```
void foo(const std::vector<X>& a1, std::vector<X>& a2)
{
  memcpy(a2.data(), a1.data(), a1.size() * sizeof(X));
}
```

Type traits: A negative overhead abstraction

```
struct X {
  int a, b, c;
  int id;
};
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

```
void foo(const std::vector<X>& a1, std::vector<X>& a2)
{
  memcpy(a2.data(), a1.data(), a1.size() * sizeof(X));
}
```

Type traits: A negative overhead abstraction

```
struct X {
  int a, b, c;
  int id;
};
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

```
void foo(const std::vector<X>& a1, std::vector<X>& a2)
{
  memcpy(a2.data(), a1.data(), a1.size() * sizeof(X));
}
```

Ooops!!!

Type traits: A negative overhead abstraction

```
struct X {
  int a, b, c;
  int id;
};
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

```
void foo(const std::vector<X>& a1, std::vector<X>& a2)
{
  std::copy(begin(a1), end(a1), begin(a2));
}
```

Type traits: A negative overhead abstraction

```
struct X {
  int a, b, c;
  int id;
};
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

```
void foo(const std::vector<X>& a1, std::vector<X>& a2)
{
  std::copy(begin(a1), end(a1), begin(a2));
}
```

```
movq    %rsi, %rax
movq    8(%rdi), %rdx
movq    (%rdi), %rsi
cmpq    %rsi, %rdx
je      .L1
movq    (%rax), %rdi
subq    %rsi, %rdx
jmp     memmove
```

```
// 100 lines of assembly code
```

Type traits: Compile-time contract

```
struct X {
  int a, b, c;
  int id;
};
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

Type traits: Compile-time contract

```
struct X {
  int a, b, c;
  int id;
};
```

```
static_assert(std::is_trivially_copyable_v<X>);
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

```
static_assert(std::is_trivially_copyable_v<X>);
```

Type traits: Compile-time contract

```
struct X {
  int a, b, c;
  int id;
};
```

```
static_assert(std::is_trivially_copyable_v<X>);
```

```
Compiler returned: 0
```

```
struct X {
  int a, b, c;
  std::string id;
};
```

```
static_assert(std::is_trivially_copyable_v<X>);
```

```
<source>:9:20: error: static assertion failed
    9 | static_assert(std::is_trivially_copyable_v<X>);
      |               ~~~~~^~~~~~~~~~~~~~~~~~~~~~~~~~
Compiler returned: 1
```

Type traits: Compile-time contract

```cpp
struct X {
  int a, b, c;
  int id;
};
```

```cpp
static_assert(std::is_trivially_copyable_v<X>);
```

```
Compiler returned: 0
```

```cpp
struct X {
  int a, b, c;
  std::string id;
};
```

```cpp
static_assert(std::is_trivially_copyable_v<X>);
```

```
<source>:9:20: error: static assertion failed
    9 | static_assert(std::is_trivially_copyable_v<X>);
      |               ~~~~~^~~~~~~~~~~~~~~~~~~~~~~~~~
Compiler returned: 1
```

Enforce compile-time contracts and class invariants with contracts or **`static_asserts`**

Type traits: Compile-time branching

```
enum class side { BID, ASK };

class order_book {
  template<side S>
  class book_side {

    std::vector<price> levels_;
  public:
    void insert(order o)
    {




    }
    bool match(price p) const
    {

    }
    // ...
  };

  book_side<side::BID> bids_;
  book_side<side::ASK> asks_;
  // ...
};
```

Type traits: Compile-time branching

```
enum class side { BID, ASK };

class order_book {
  template<side S>
  class book_side {
    using compare = std::conditional_t<S == side::BID, std::greater<>, std::less<>>;
    std::vector<price> levels_;
  public:
    void insert(order o)
    {




    }
    bool match(price p) const
    {

    }
    // ...
  };

  book_side<side::BID> bids_;
  book_side<side::ASK> asks_;
  // ...
};
```

Type traits: Compile-time branching

```
enum class side { BID, ASK };

class order_book {
  template<side S>
  class book_side {
    using compare = std::conditional_t<S == side::BID, std::greater<>, std::less<>>;
    std::vector<price> levels_;
  public:
    void insert(order o)
    {
      const auto it = lower_bound(begin(levels_), end(levels_), o.price, compare{});
      if(it != end(levels_) && *it != o.price)
        levels_.insert(it, o.price);
      // ...
    }
    bool match(price p) const
    {

    }
    // ...
  };

  book_side<side::BID> bids_;
  book_side<side::ASK> asks_;
  // ...
};
```

Type traits: Compile-time branching

```
enum class side { BID, ASK };

class order_book {
  template<side S>
  class book_side {
    using compare = std::conditional_t<S == side::BID, std::greater<>, std::less<>>;
    std::vector<price> levels_;
  public:
    void insert(order o)
    {
      const auto it = lower_bound(begin(levels_), end(levels_), o.price, compare{});
      if(it != end(levels_) && *it != o.price)
        levels_.insert(it, o.price);
      // ...
    }
    bool match(price p) const
    {
      return compare{}(levels_.back(), p);
    }
    // ...
  };

  book_side<side::BID> bids_;
  book_side<side::ASK> asks_;
  // ...
};
```

What is wrong here?

```
constexpr int array_size = 10'000;
int array[array_size][array_size];

for(auto i = 0L; i < array_size; ++i) {
  for(auto j = 0L; j < array_size; ++j) {
    array[j][i] = i + j;
  }
}
```

What is wrong here?

```
constexpr int array_size = 10'000;
int array[array_size][array_size];

for(auto i = 0L; i < array_size; ++i) {
  for(auto j = 0L; j < array_size; ++j) {
    array[j][i] = i + j;
  }
}
```

Reckless cache usage can cost you a lot of performance!

Quiz: How much slower is the bad case?

```
Architecture:                    x86_64
CPU op-mode(s):                  32-bit, 64-bit
Byte Order:                      Little Endian
Address sizes:                   39 bits physical, 48 bits virtual
CPU(s):                          8
On-line CPU(s) list:             0-7
Thread(s) per core:              2
Core(s) per socket:              4
Socket(s):                       1
NUMA node(s):                    1
Vendor ID:                       GenuineIntel
CPU family:                      6
Model:                           142
Model name:                      Intel(R) Core(TM) i5-8350U CPU @ 1.70GHz
Stepping:                        10
CPU MHz:                         1700.035
CPU max MHz:                     1700,0000
CPU min MHz:                     400,0000
BogoMIPS:                        3799.90
Virtualization:                  VT-x
L1d cache:                       128 KiB
L1i cache:                       128 KiB
L2 cache:                        1 MiB
L3 cache:                        6 MiB
NUMA node0 CPU(s):               0-7
```

Quiz: How much slower is the bad case?

Please everybody stand up :-)

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**
- **< 20x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**
- **< 20x**
- **< 50x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**
- **< 20x**
- **< 50x**
- **< 100x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**
- **< 20x**
- **< 50x**
- **< 100x**
- **>= 100x**

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**
- **< 20x**
- **< 50x**
- **< 100x**
- **>= 100x**

GCC 7.4.0

- column-major: 2490 ms
- row-major: 51 ms
- ratio: 47x

Quiz: How much slower is the bad case?

Please everybody stand up :-)

- Similar
- **< 2x**
- **< 5x**
- **< 10x**
- **< 20x**
- **< 50x**
- **< 100x**
- **>= 100x**

GCC 7.4.0

- column-major: **2490 ms**
- row-major: **51 ms**
- **ratio: 47x**

GCC 9.2.1

- column-major: **51 ms**
- row-major: **50 ms**
- **ratio: Similar :-)**

CPU data cache

```
     3 274,28 msec task-clock                #    0,999 CPUs utilized
 5 536 529 085      cycles                    #    1,691 GHz                      (66,53%)
 1 246 414 976      instructions              #    0,23  insn per cycle           (83,27%)
    92 872 234      L1-dcache-loads           #   28,364 M/sec                    (83,29%)
   410 636 090      L1-dcache-load-misses     #  442,15% of all L1-dcache hits    (83,39%)
    87 191 333      LLC-loads                 #   26,629 M/sec                    (83,39%)
       527 256      LLC-load-misses           #    0,60% of all LL-cache hits    (83,41%)
        97 781      page-faults               #    0,030 M/sec
```

```
      360,48 msec task-clock                #    0,999 CPUs utilized
   609 105 177      cycles                    #    1,690 GHz                      (66,71%)
   891 120 837      instructions              #    1,46  insn per cycle           (83,36%)
    90 219 862      L1-dcache-loads           #  250,279 M/sec                    (83,35%)
    14 481 217      L1-dcache-load-misses     #   16,05% of all L1-dcache hits    (83,35%)
       167 850      LLC-loads                 #    0,466 M/sec                    (83,36%)
        79 492      LLC-load-misses           #   47,36% of all LL-cache hits    (83,22%)
        97 783      page-faults               #    0,271 M/sec
```

CPU data cache

```
     3 274,28 msec task-clock                #    0,999 CPUs utilized
5 536 529 085      cycles                    #    1,691 GHz                      (66,53%)
1 246 414 976      instructions              #    0,23  insn per cycle           (83,27%)
   92 872 234      L1-dcache-loads           #   28,364 M/sec                    (83,29%)
  410 636 090      L1-dcache-load-misses     #  442,15% of all L1-dcache hits    (83,39%)
   87 191 333      LLC-loads                 #   26,629 M/sec                    (83,39%)
      527 256      LLC-load-misses           #    0,60% of all LL-cache hits    (83,41%)
       97 781      page-faults               #    0,030 M/sec
```

```
      360,48 msec task-clock                #    0,999 CPUs utilized
  609 105 177      cycles                    #    1,690 GHz                      (66,71%)
  891 120 837      instructions              #    1,46  insn per cycle           (83,36%)
   90 219 862      L1-dcache-loads           #  250,279 M/sec                    (83,35%)
   14 481 217      L1-dcache-load-misses     #   16,05% of all L1-dcache hits    (83,35%)
      167 850      LLC-loads                 #    0,466 M/sec                    (83,36%)
       79 492      LLC-load-misses           #   47,36% of all LL-cache hits    (83,22%)
       97 783      page-faults               #    0,271 M/sec
```

CPU data cache

```
     3 274,28 msec task-clock                #    0,999 CPUs utilized
 5 536 529 085      cycles                    #    1,691 GHz                      (66,53%)
 1 246 414 976      instructions              #    0,23  insn per cycle           (83,27%)
    92 872 234      L1-dcache-loads           #   28,364 M/sec                    (83,29%)
   410 636 090      L1-dcache-load-misses     #  442,15% of all L1-dcache hits    (83,39%)
    87 191 333      LLC-loads                 #   26,629 M/sec                    (83,39%)
       527 256      LLC-load-misses           #    0,60% of all LL-cache hits    (83,41%)
        97 781      page-faults               #    0,030 M/sec
```

```
      360,48 msec task-clock                #    0,999 CPUs utilized
   609 105 177      cycles                    #    1,690 GHz                      (66,71%)
   891 120 837      instructions              #    1,46  insn per cycle           (83,36%)
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        97 783      page-faults               #    0,271 M/sec
```

Another example

```
struct coordinates { int x, y; };

void draw(const coordinates& coord);
void verify(int threshold);

constexpr int OBJECT_COUNT = 1'000'000;
class objectMgr;

void process(const objectMgr& mgr)
{
  const auto size = mgr.size();
  for(auto i = 0UL; i < size; ++i) { draw(mgr.position(i)); }
  for(auto i = 0UL; i < size; ++i) { verify(mgr.threshold(i)); }
}
```

Naive objectMgr implementation

```
class objectMgr {
  struct object {
    coordinates coord;
    std::string errorTxt_1;
    std::string errorTxt_2;
    std::string errorTxt_3;
    int threshold;
    std::array<char, 100> otherData;
  };
  std::vector<object> data_;

public:
  explicit objectMgr(std::size_t size) : data_{size} {}
  std::size_t size() const                              { return data_.size(); }
  const coordinates& position(std::size_t idx) const { return data_[idx].coord; }
  int threshold(std::size_t idx) const                  { return data_[idx].threshold; }
};
```

Naive objectMgr implementation

```
class objectMgr {
  struct object {
    coordinates coord;
    std::string errorTxt_1;
    std::string errorTxt_2;
    std::string errorTxt_3;
    int threshold;
    std::array<char, 100> otherData;
  };
  std::vector<object> data_;

public:
  explicit objectMgr(std::size_t size) : data_{size} {}
  std::size_t size() const                              { return data_.size(); }
  const coordinates& position(std::size_t idx) const { return data_[idx].coord; }
  int threshold(std::size_t idx) const                  { return data_[idx].threshold; }
};
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DOD (Data-Oriented Design)

- Program optimization approach motivated by cache coherency
- Focuses on data layout
- Results in objects decomposition

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- Program optimization approach motivated by cache coherency
- **Focuses on data layout**
- Results in objects decomposition

Keep data used together close to each other

Object decomposition example

```
class objectMgr {
  std::vector<coordinates> positions_;
  std::vector<int> thresholds_;

  struct otherData {
    struct errorData { std::string errorTxt_1, errorTxt_2, errorTxt_3; };
    errorData error;
    std::array<char, 100> data;
  };
  std::vector<otherData> coldData_;

public:
  explicit objectMgr(std::size_t size) :
    positions_{size}, thresholds_(size), coldData_{size} {}
  std::size_t size() const                                { return positions_.size(); }
  const coordinates& position(std::size_t idx) const      { return positions_[idx]; }
  int threshold(std::size_t idx) const                    { return thresholds_[idx]; }
};
```

Members order might be important

```
struct A {
  char c;
  short s;
  int i;
  double d;
  static double dd;
};

static_assert( sizeof(A) == ??);
static_assert(alignof(A) == ??);
```

```
struct B {
  char c;
  double d;
  short s;
  int i;
  static double dd;
};

static_assert( sizeof(B) == ??);
static_assert(alignof(B) == ??);
```

Members order might be important

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```
struct B {
  char c;     // size=1, alignment=1, padding=7
  double d;   // size=8, alignment=8, padding=0
  short s;    // size=2, alignment=2, padding=2
  int i;      // size=4, alignment=4, padding=0
  static double dd;
};

static_assert( sizeof(B) == 24);
static_assert(alignof(B) == 8);
```

Members order might be important

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```
struct B {
  char c;     // size=1, alignment=1, padding=7
  double d;   // size=8, alignment=8, padding=0
  short s;    // size=2, alignment=2, padding=2
  int i;      // size=4, alignment=4, padding=0
  static double dd;
};

static_assert( sizeof(B) == 24);
static_assert(alignof(B) == 8);
```

In order to satisfy alignment requirements of all non-static members of a class, padding may be inserted after some of its members

Be aware of alignment side effects

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

Be aware of alignment side effects

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```
using opt = std::optional<A>;

static_assert( sizeof(opt) == 24);
static_assert(alignof(opt) == 8);
```

Be aware of alignment side effects

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```
using opt = std::optional<A>;

static_assert( sizeof(opt) == 24);
static_assert(alignof(opt) == 8);
```

```
using array = std::array<opt, 256>;

static_assert( sizeof(array) == 24 * 256);
static_assert(alignof(array) == 8);
```

Be aware of alignment side effects

```cpp
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```cpp
using opt = std::optional<A>;

static_assert( sizeof(opt) == 24);
static_assert(alignof(opt) == 8);
```

```cpp
using array = std::array<opt, 256>;

static_assert( sizeof(array) == 24 * 256);
static_assert(alignof(array) == 8);
```

Be aware of implementation details of the tools you use every day

Packing

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```
struct C {
  char c;
  double d;
  short s;
  static double dd;
  int i;
} __attribute__((packed));

static_assert( sizeof(C) == 15);
static_assert(alignof(C) == 1);
```

Packing

```
struct A {
  char c;     // size=1, alignment=1, padding=1
  short s;    // size=2, alignment=2, padding=0
  int i;      // size=4, alignment=4, padding=0
  double d;   // size=8, alignment=8, padding=0
  static double dd;
};

static_assert( sizeof(A) == 16);
static_assert(alignof(A) == 8);
```

```
struct C {
  char c;
  double d;
  short s;
  static double dd;
  int i;
} __attribute__((packed));

static_assert( sizeof(C) == 15);
static_assert(alignof(C) == 1);
```

On modern hardware may be faster than aligned structure

Packing

```
struct A {
  char c;     // size=1, alignment=1, padding=1
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};

static_assert( sizeof(A) == 16);
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struct C {
  char c;
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  int i;
} __attribute__((packed));

static_assert( sizeof(C) == 15);
static_assert(alignof(C) == 1);
```

On modern hardware may be faster than aligned structure

Not portable! May be slower or even crash

Latency Numbers Every Programmer Should Know

L1 cache reference	0.5	ns		
Branch misprediction	5	ns		
L2 cache reference	7	ns		14x L1 cache
Mutex lock/unlock	25	ns		
Main memory reference	100	ns		20x L2 cache, 200x L1 cache
Compress 1K bytes with Zippy	3,000	ns		
Send 1K bytes over 1 Gbps network	10,000	ns	0.01 ms	
Read 4K randomly from SSD	150,000	ns	0.15 ms	~1GB/sec SSD
Read 1 MB sequentially from memory	250,000	ns	0.25 ms	
Round trip within same datacenter	500,000	ns	0.5 ms	
Read 1 MB sequentially from SSD	1,000,000	ns	1 ms	~1GB/sec SSD, 4X memory
Disk seek	10,000,000	ns	10 ms	20x datacenter roundtrip
Read 1 MB sequentially from disk	20,000,000	ns	20 ms	80x memory, 20X SSD
Send packet CA->Netherlands->CA	150,000,000	ns	150 ms	

https://gist.github.com/jboner/2841832

What is wrong here?

```
class vector_downward {
  uint8_t *make_space(size_t len) {
    if(len > static_cast<size_t>(cur_ - buf_)) {
      auto old_size = size();
      auto largest_align = AlignOf<largest_scalar_t>();
      reserved_ += (std::max)(len, growth_policy(reserved_));
      // Round up to avoid undefined behavior from unaligned loads and stores.
      reserved_ = (reserved_ + (largest_align - 1)) & ~(largest_align - 1);
      auto new_buf = allocator_.allocate(reserved_);
      auto new_cur = new_buf + reserved_ - old_size;
      memcpy(new_cur, cur_, old_size);
      cur_ = new_cur;
      allocator_.deallocate(buf_);
      buf_ = new_buf;
    }
    cur_ -= len;
    // Beyond this, signed offsets may not have enough range:
    // (FlatBuffers > 2GB not supported).
    assert(size() < FLATBUFFERS_MAX_BUFFER_SIZE);
    return cur_;
  }
  // ...
};
```

What is wrong here?

```
class vector_downward {
  uint8_t *make_space(size_t len) {
    if(len > static_cast<size_t>(cur_ - buf_)) {
      auto old_size = size();
      auto largest_align = AlignOf<largest_scalar_t>();
      reserved_ += (std::max)(len, growth_policy(reserved_));
      // Round up to avoid undefined behavior from unaligned loads and stores.
      reserved_ = (reserved_ + (largest_align - 1)) & ~(largest_align - 1);
      auto new_buf = allocator_.allocate(reserved_);
      auto new_cur = new_buf + reserved_ - old_size;
      memcpy(new_cur, cur_, old_size);
      cur_ = new_cur;
      allocator_.deallocate(buf_);
      buf_ = new_buf;
    }
    cur_ -= len;
    // Beyond this, signed offsets may not have enough range:
    // (FlatBuffers > 2GB not supported).
    assert(size() < FLATBUFFERS_MAX_BUFFER_SIZE);
    return cur_;
  }
  // ...
};
```

Separate the code to hot and cold paths

```
class vector_downward {
  uint8_t *make_space(size_t len) {
    if(len > static_cast<size_t>(cur_ - buf_))
      reallocate(len);
    cur_ -= len;
    // Beyond this, signed offsets may not have enough range:
    // (FlatBuffers > 2GB not supported).
    assert(size() < FLATBUFFERS_MAX_BUFFER_SIZE);
    return cur_;
  }

  void reallocate(size_t len) {
    auto old_size = size();
    auto largest_align = AlignOf<largest_scalar_t>();
    reserved_ += (std::max)(len, growth_policy(reserved_));
    // Round up to avoid undefined behavior from unaligned loads and stores.
    reserved_ = (reserved_ + (largest_align - 1)) & ~(largest_align - 1);
    auto new_buf = allocator_.allocate(reserved_);
    auto new_cur = new_buf + reserved_ - old_size;
    memcpy(new_cur, cur_, old_size);
    cur_ = new_cur;
    allocator_.deallocate(buf_);
    buf_ = new_buf;
  }
  // ...
};
```

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  }
  // ...
};
```

Code is data too!

Separate the code to hot and cold paths

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    assert(size() < FLATBUFFERS_MAX_BUFFER_SIZE);
    return cur_;
  }
  // ...
};
```

Code is data too!

Performance improvement of 20% thanks to a better inlining

Typical validation and error handling

```
std::optional<Error> validate(const request& r)
{
  switch(r.type) {
  case request::type_1:
    if(/* simple check */)
      return std::nullopt;
    return /* complex error msg generation */;
  case request::type_2:
    if(/* simple check */)
      return std::nullopt;
    return /* complex error msg generation */;
  case request::type_3:
    if(/* simple check */)
      return std::nullopt;
    return /* complex error msg generation */;
  // ...
  }
  throw std::logic_error("");
}
```

Isolating cold path

```
std::optional<Error> validate(const request& r)
{
  if(is_valid(r))
    return std::nullopt;
  return make_error(r)
}
```

Isolating cold path

```
std::optional<Error> validate(const request& r)
{
  if(is_valid(r))
    return std::nullopt;
  return make_error(r)
}
```

```
bool is_valid(const request& r)
{
  switch(r.type) {
  case request::type_1:
    return /* simple check */;
  case request::type_2:
    return /* simple check */;
  case request::type_3:
    return /* simple check */;
  // ...
  }
  throw std::logic_error("");
}
```

Isolating cold path

```
std::optional<Error> validate(const request& r)
{
  if(is_valid(r))
    return std::nullopt;
  return make_error(r)
}
```

```
bool is_valid(const request& r)
{
  switch(r.type) {
  case request::type_1:
    return /* simple check */;
  case request::type_2:
    return /* simple check */;
  case request::type_3:
    return /* simple check */;
  // ...
  }
  throw std::logic_error("");
}
```

```
Error make_error(const request& r)
{
  switch(r.type) {
  case request::type_1:
    return /* complex error msg generation */;
  case request::type_2:
    return /* complex error msg generation */;
  case request::type_3:
    return /* complex error msg generation */;
  // ...
  }
  throw std::logic_error("");
}
```

Expression short-circuiting

WRONG

```
if(expensiveCheck() && fastCheck()) { /* ... */ }
```

GOOD

```
if(fastCheck() && expensiveCheck()) { /* ... */ }
```

Expression short-circuiting

WRONG

```
if(expensiveCheck() && fastCheck()) { /* ... */ }
```

GOOD

```
if(fastCheck() && expensiveCheck()) { /* ... */ }
```

Bail out as early as possible and continue fast path

Integer arithmetic

```
int foo(int i)
{
  int k = 0;
  for(int j = i; j < i + 10; ++j)
    ++k;
  return k;
}
```

```
int foo(unsigned i)
{
  int k = 0;
  for(unsigned j = i; j < i + 10; ++j)
    ++k;
  return k;
}
```

Integer arithmetic

```
int foo(int i)
{
  int k = 0;
  for(int j = i; j < i + 10; ++j)
    ++k;
  return k;
}
```

```
foo(int):
        mov     eax, 10
        ret
```

```
int foo(unsigned i)
{
  int k = 0;
  for(unsigned j = i; j < i + 10; ++j)
    ++k;
  return k;
}
```

```
foo(unsigned int):
        cmp     edi, -10
        sbb     eax, eax
        and     eax, 10
        ret
```

Integer arithmetic

```
int foo(int i)
{
  int k = 0;
  for(int j = i; j < i + 10; ++j)
    ++k;
  return k;
}
```

```
foo(int):
        mov     eax, 10
        ret
```

```
int foo(unsigned i)
{
  int k = 0;
  for(unsigned j = i; j < i + 10; ++j)
    ++k;
  return k;
}
```

```
foo(unsigned int):
        cmp     edi, -10
        sbb     eax, eax
        and     eax, 10
        ret
```

Integer arithmetic differs for the signed and unsigned integral types

How to develop system with low-latency constraints

- Avoid using **`std::list`**, **`std::map`**, etc

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- **`std::unordered_map`** is also broken
- Prefer **`std::vector`**
  - also as the underlying storage for hash tables or flat maps
  - consider using **`tsl::hopscotch_map`**, Swiss Tables, F14 hash map, or similar

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- Preallocate storage
  - free list
  - **`plf::colony`**

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- Consider storing only pointers to objects in the container
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- Preallocate storage
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  - **`plf::colony`**
- Consider storing only pointers to objects in the container
- Consider storing expensive hash values with the key
- Limit the number of *type conversions*

How to develop system with low-latency constraints

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- Keep the **number of threads** close (less or equal) to the number of available *physical CPU cores*

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- **Measure** performance… **ALWAYS**

The most important recommendation

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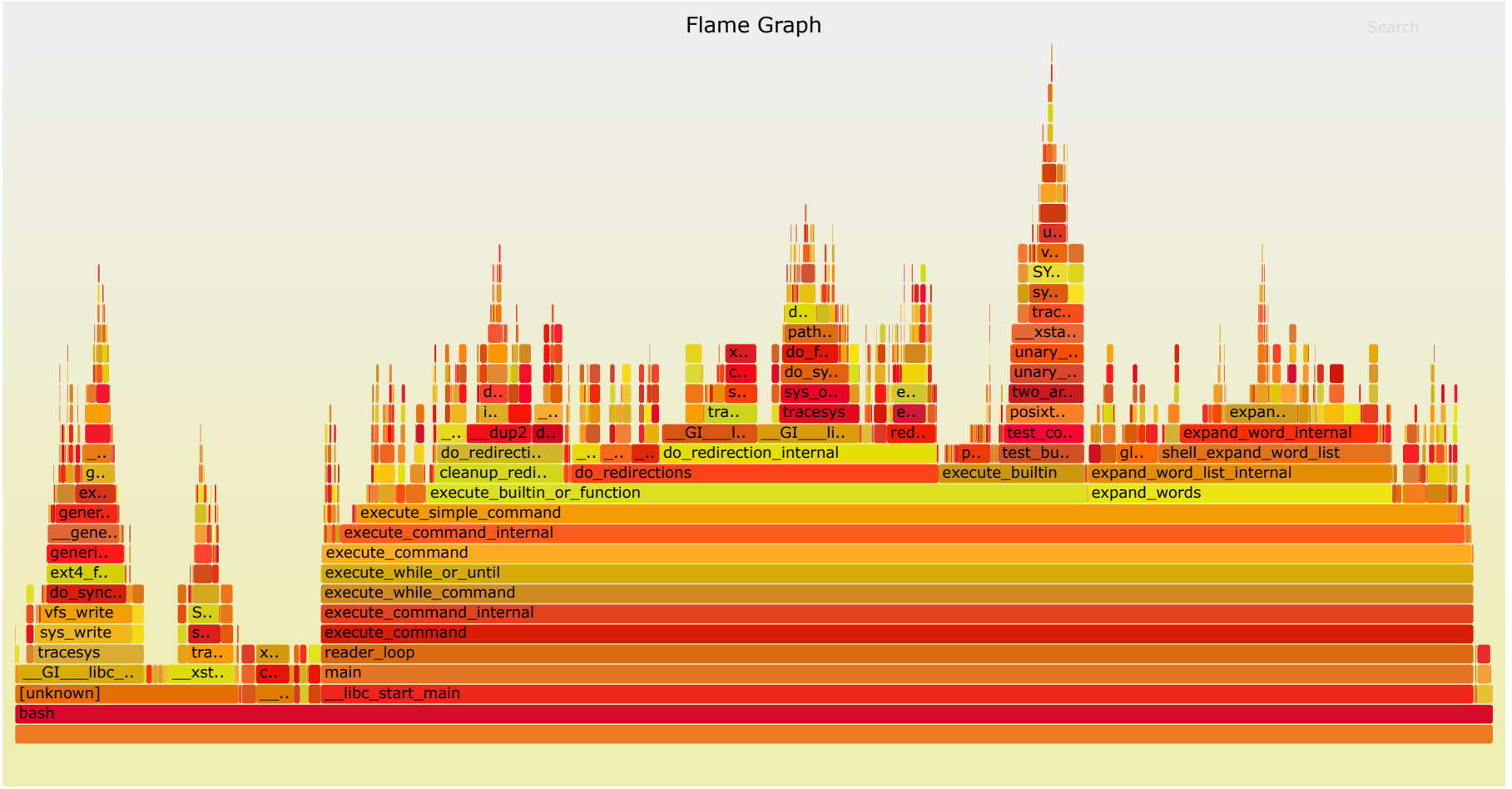
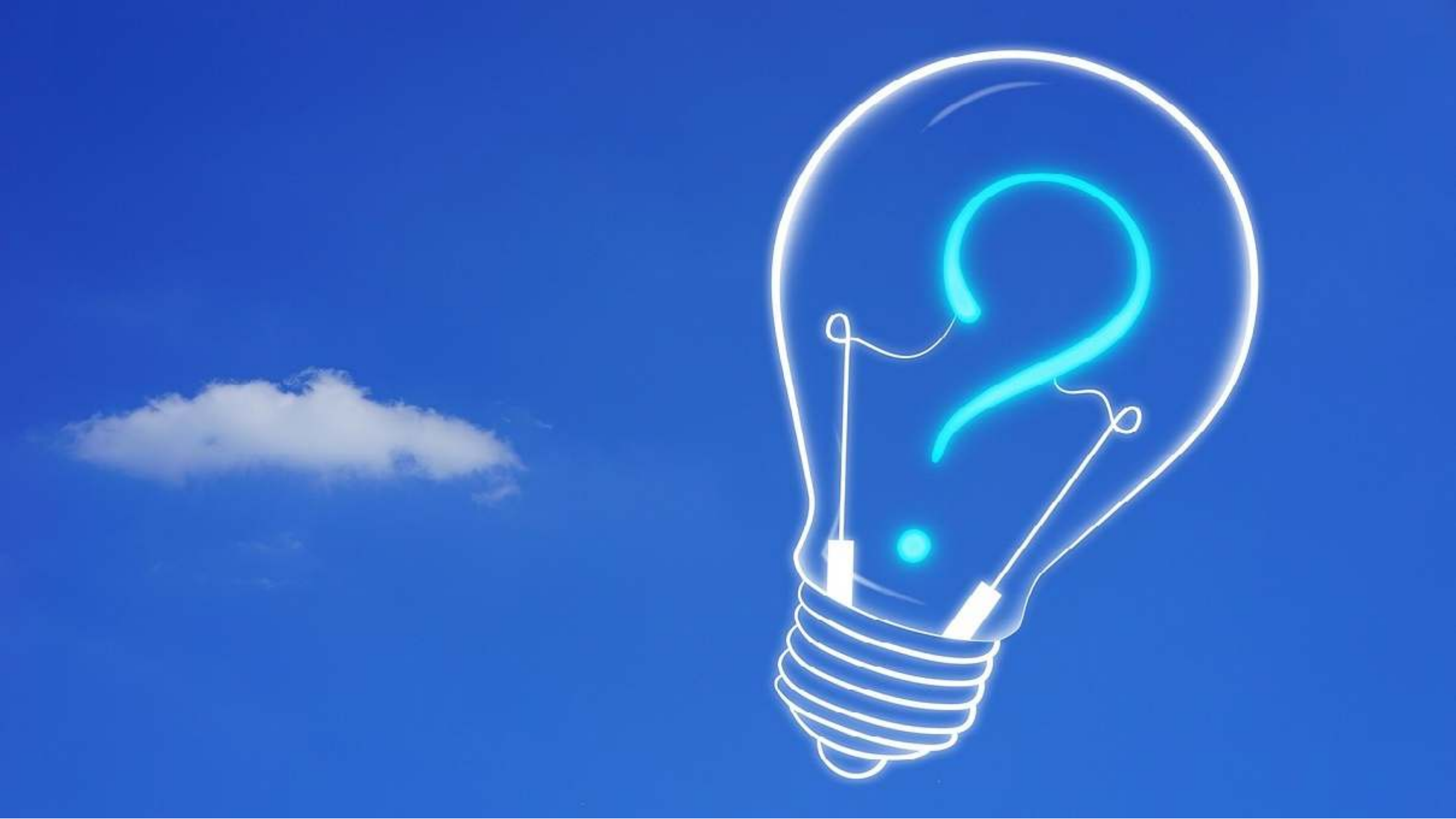
- *Verify output assembly code*

Flamegraph


Flame Graph
Search
u..
v..
SY..
sy..
trac..
__xsta..
unary_..
unary_..
two_ar..
posixt..
test_co..
test_bu..
p..
execute_builtin
expand_words
gl..
expand_word_list_internal
shell_expand_word_list
expan..
expand_word_internal
d..
path..
do_f..
do_sy..
sys_o..
tracesys
red..
e..
e..
x..
c..
s..
tra..
__GI___l..
__GI___li..
do_redirection_internal
_.. _.. _..
do_redirections
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
bash
d..
i..
_..
_..
__dup2
d..
do_redirecti..
cleanup_redi..
g..
ex..
gener..
__gene..
generi..
ext4_f..
do_sync..
vfs_write
sys_write
tracesys
__GI___libc_..
[unknown]
S..
s..
tra..
__xst..
x..
c..
__..




CAUTION
Programming
is addictive
(and too much fun)