Sane and Safe C++ Class Types

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CPPCon September 2018

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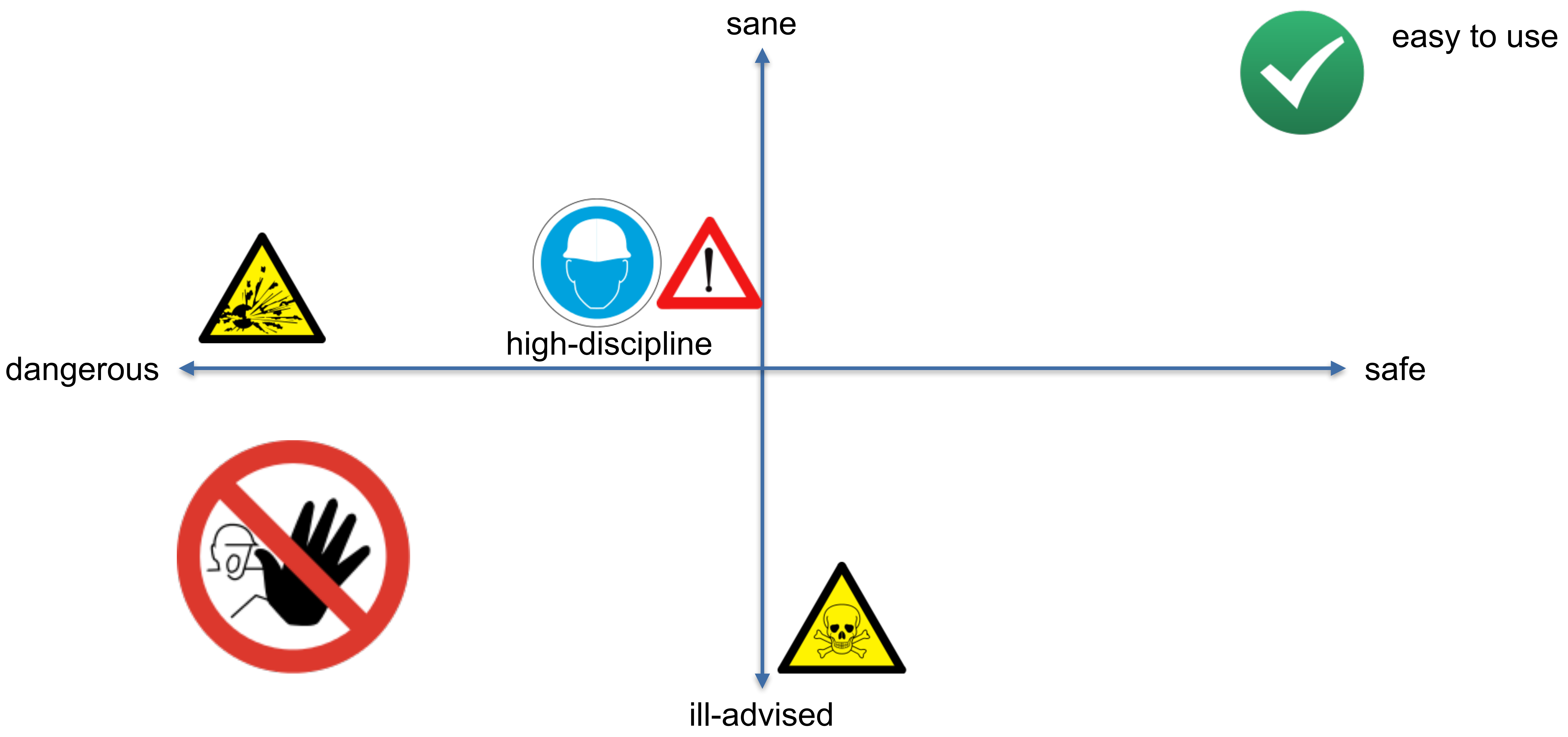
Dimensions Safety and Sanity...



Values

"When in doubt, do as the ints do!"
-- Scott Meyers

"But may be not always…"
-- Peter Sommerlad

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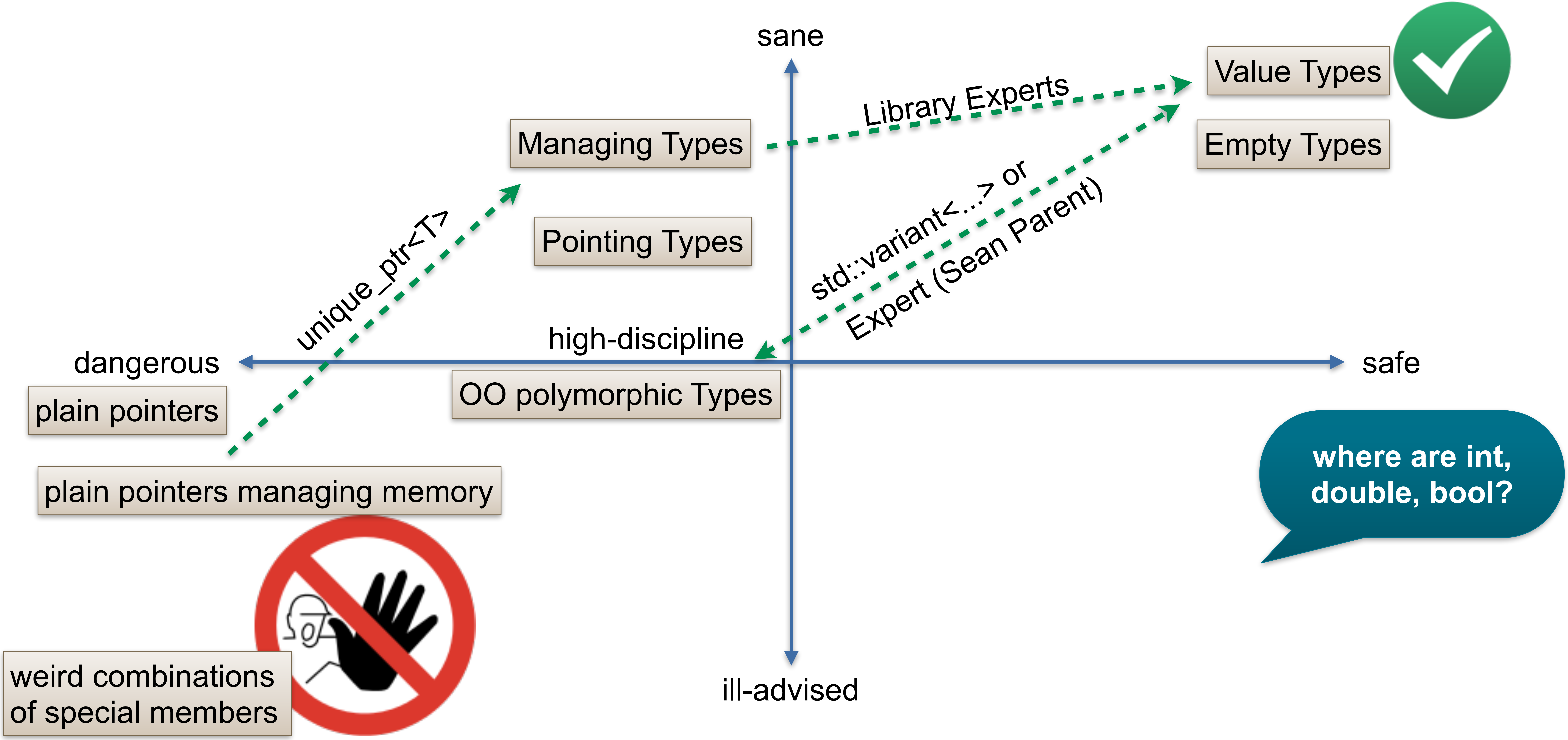
C++ standard containers assume (semi-)regular types as template arguments for elements.
They might work with non-default constructible or move-only types but with limited functionality.

- **Properties of types satisfying concept Regular<T>**
  - EqualityComparable (==, !=)
  - DefaultConstructible T{}
  - Copyable T(T const&), T& operator=(T const&)&,
  - Movable T(T&&), T& operator=(T&&)&, is_object_v
  - Swappable swap(T&,T&)
  - Assignable t1 = t2
  - MoveConstructible T(T&&)

Sometimes Ordering is also required
std::less<T> should work,
usually by defining
bool operator<(T,T)

If comparison works, it should be consistent!
C++20 will make that more easy, through the "spaceship" operator<=>

Value (class) Types are Sane and Safe!



- **Safety: int, char, bool, double are Regular value types, OK**
  - copying, equality is given
- **BUT:**

```
void InsaneBool() {
  using namespace std::string_literals;
  auto const i { 41 };
  bool const throdd = i % 3;
  auto const theanswer= (throdd & (i+1) ) ? "yes"s : "no"s;
  ASSERT_EQUAL("",theanswer);
}
```

What makes the test run?

- **Safety: int, char, bool, double are Regular value types, OK**
  - copying, equality is given
- **BUT:**

```
void InterestingSetDouble(){
  std::vector v{0.0,0.01,0.2,3.0};
  std::set<double> s{};
  for (auto x:v){
    for (auto y:v)
      s.insert(x/y);
  }
  ASSERT_EQUAL(v.size()*v.size()-v.size()+1,s.size()); // really?
}
```

What is the size?

Are library types "sane" and "safe"?

- **Safety: containers are Regular value types, if their elements and other template arguments are.**
  - copying, equality is given
- **BUT: they still use built-in types resulting in interesting behavior**

```
void printBackwards(std::ostream &out, std::vector<int> const &v){
  for(auto i=v.size() - 1; i >= 0; --i)
    out << v[i] << " ";
}
```

Can you spot the bug!

Some of the Problems with **primitive** built-in types

- **Integral promotion (inherited from C)**
  - with very interesting rules no one can remember correctly, including bool and char as integer types
  - signed - unsigned mixtures in arithmetic
  - silent wrapping vs. undefined behavior on overflow, vs. signaling of overflow (want the carry bit!)

warnings often silenced with arbitrary casts

- **Automatic (numeric) conversions**
  - integers <-> floating points <-> bool
  - and that complicated with types with non-explicit constructors and conversion operators

Do not make your class types implicitly convert!

- **Special values for floating point numbers**
  - +Inf, -Inf, NaN (often forgotten)

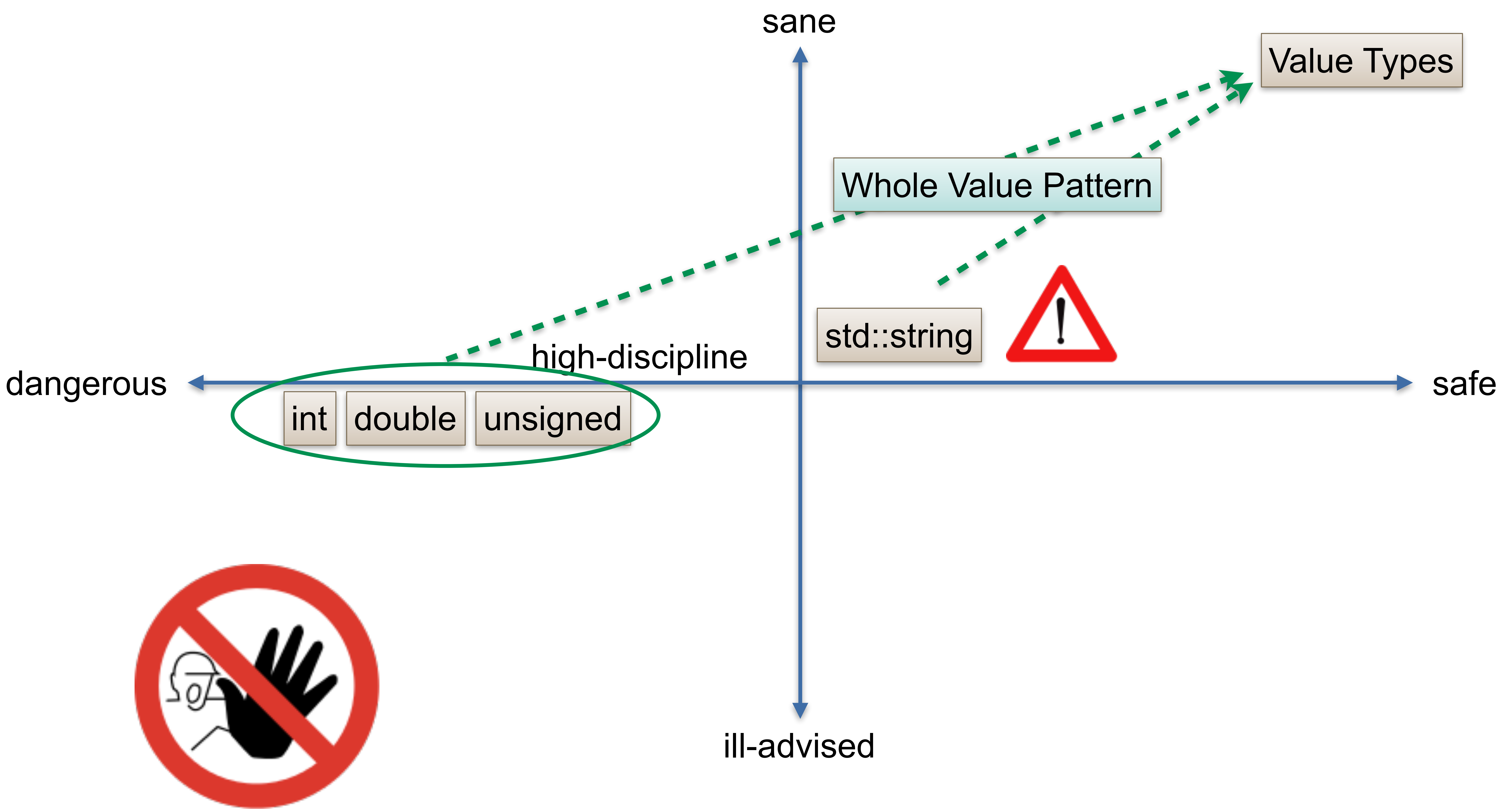
Make comparison strict weak order or stronger!

- **Consciously wrap primitive, or built-in types into types with meaning to the application**
  - fluximate(int,int,int) is hard to call correctly! fluximate(3,2,1) or fluximate(1,2,3)
    - BTW: Named Parameters are only curing a symptom (IMHO in the wrong way)!
  - C++ can do so without (significant) run-time overhead
- **Standard library is guilty of using built-ins as type aliases where they do not fit nicely**
  - size_t, size_type --> count elements = natural numbers including 0 - **absolute value**

```
    size_type __n = std::distance(__first, __last); // implicit conversion to unsigned
     if (capacity() - size() >= __n) // aha to avoid warning in comparison
      {
  std::copy_backward(__position, end(),
         this->_M_impl._M_finish
         + difference_type(__n)); // cast to the real thing again
  std::copy(__first, __last, __position);
  this->_M_impl._M_finish += difference_type(__n); // and cast again!
      }
```

warnings often silenced with arbitrary casts

Dimensions Safety and Sanity...



```
check_counters(0,1);// which is which?
```

- Parameters can be confusing, when multiple parameters of the same type occur.
- Names can help, but...
- Some time ago, an IFS assistant searched for a bug, where two arguments were in the wrong order

```
void check_counters(size_t waits, size_t notifies);
```

- Type aliases as in the standard library are no solution:

```
using WaitCounter=size_t;
using NotifyCounter=size_t;
void check_counters(WaitCounter w, NotifyCounter n);
```

- Need: "Strong" Type Aliases - each role/usage gets its own type that is not a primitive type

- *When parameterizing or otherwise quantifying a business (domain) model there remains an overwhelming desire to express these parameters in the most fundamental units of computation.*

like C

  - *Not only is this no longer necessary (it was standard practice in languages with weak or no abstraction), it actually interferes with smooth and proper communication between the parts of your program and with its users.*
  - *Because bits, strings and numbers can be used to* ***represent almost anything****, any one in isolation* ***means*** *almost* ***nothing****.*
- **Therefore:**
- *Construct specialized values to quantify your domain model and use these values as the* ***arguments*** *of their messages and as the units of input and output.*

Value Types

  - *Make sure these objects capture the whole quantity with all its implications beyond merely magnitude, but, keep them independent of any particular domain.*

functions, operators

  - *Include format converters in your user-interface that can correctly and reliably construct these objects on input and print them on output.*

constructors, I/O

  - ***Do not expect your domain model to handle string or numeric representations of the same information.***

no implicit conversions

Whole Value Pattern in the most simple way: just define a struct type

```
check_counters(Wait{0},Notify{2});
```

Aggregate Initialization: structtype{members}

- **Documents which counter has which role at call site (note: no implicit constructors!)**
- **Overloading is possible to allow more flexibility (but not necessarily recommended)**

```
void check_counters(Wait w, Notify n);
```

- **Define a struct/class wrapping the simple type (with required operators):**

```
struct Wait {
  size_t count{};
}; // minimal version
```

The simplest strong type version

```
void operator++(Wait &w){ // retrofit increment for use case
  w.count++;
}
```

Should I make a (whole) value type default-constructible? T()=default;

- **Yes, whenever there is a natural default or neutral value in your type's domain**
  - int{} == 0
  - Be aware that the neutral value can depend on the major operation: int{} is not good for multiplication
- **May be, when initialization can be conditional and you need to define a variable first**
  - consider learning how to use ?: operator or an in-place called lambda, requires assignability otherwise
- **No, when there is not natural default value**
  - PokerCard (2-10, J, Q, K, Ace of ♤♧♡♢) What should be the default? - no default constructor!
- **No, when the type's invariant requires a reasonable initialization**
  - e.g., class CryptographicKey --> to be useful needs real key data

Units beware: relative vs. absolute - often misunderstood or easily misapplied

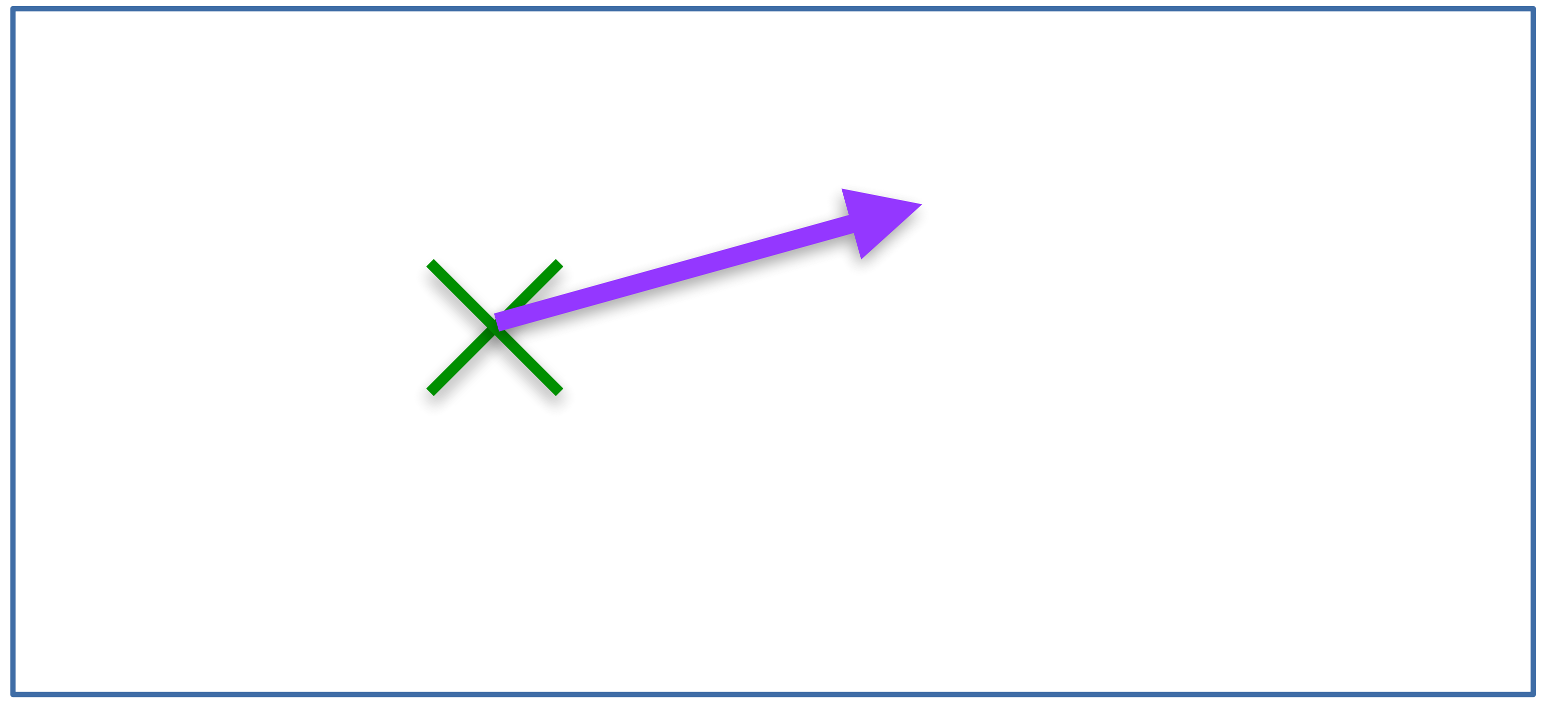
relative

relative

```
size_type __n = std::distance(__first, __last); // implicit conversion to unsigned
 if (capacity() - size() >= __n) // aha to avoid warning in comparison
  {
std::copy_backward(__position, end(),
        this->_M_impl._M_finish
        + difference_type(__n)); // cast to the real thing again
std::copy(__first, __last, __position);
this->_M_impl._M_finish += difference_type(__n); // and cast again!
```

wrong result type!

- **<chrono> is a good example to follow:**
    - time_point and duration: tp1 - tp2 -> duration, tp + d -> time_point, **tp+tp -> nonsense**, d1 + d2 -> duration
- **position vs. direction**
    - Vec3d/Vec3 and similar are problematic, because identical representation is used for both roles
    - location and displacement
- **generic units must make this distinction**
    - easily forgotten in dimensional analysis



```
struct WaitC:strong<unsigned,WaitC>
            ,ops<WaitC,Eq,Inc,Out>{};
static_assert(sizeof(unsigned)==sizeof(WaitC));

void testWaitCounter(){
  WaitC c{};
  WaitC const one{1};
  ASSERT_EQUAL(WaitC{0},c);
  ASSERT_EQUAL(one,++c);
  ASSERT_EQUAL(one,c++);
  ASSERT_EQUAL(2,c.get());
}
```

CRTP

EBO

- **see video presentations and libraries by**
- **Björn Fahller (ACCU2018)**
- **Jonathan Boccara**
- **Jonathan Müller**
- **Me: PSST - Peter's simple strong typing**
  - uses aggregates and CRTP mix-ins (work in progress)
- **IMHO, "Strong Typing" frameworks/infrastructure are often too generic.**
- **Aggregate types are OK -> Rule of Zero, No automatic conversion, unless specified!**
  - If there is no invariant to be ensured, ie., all member-type values are valid
  - C++17 allows operations to be CRTP-mixed-in without space overhead, if first base contains actual value

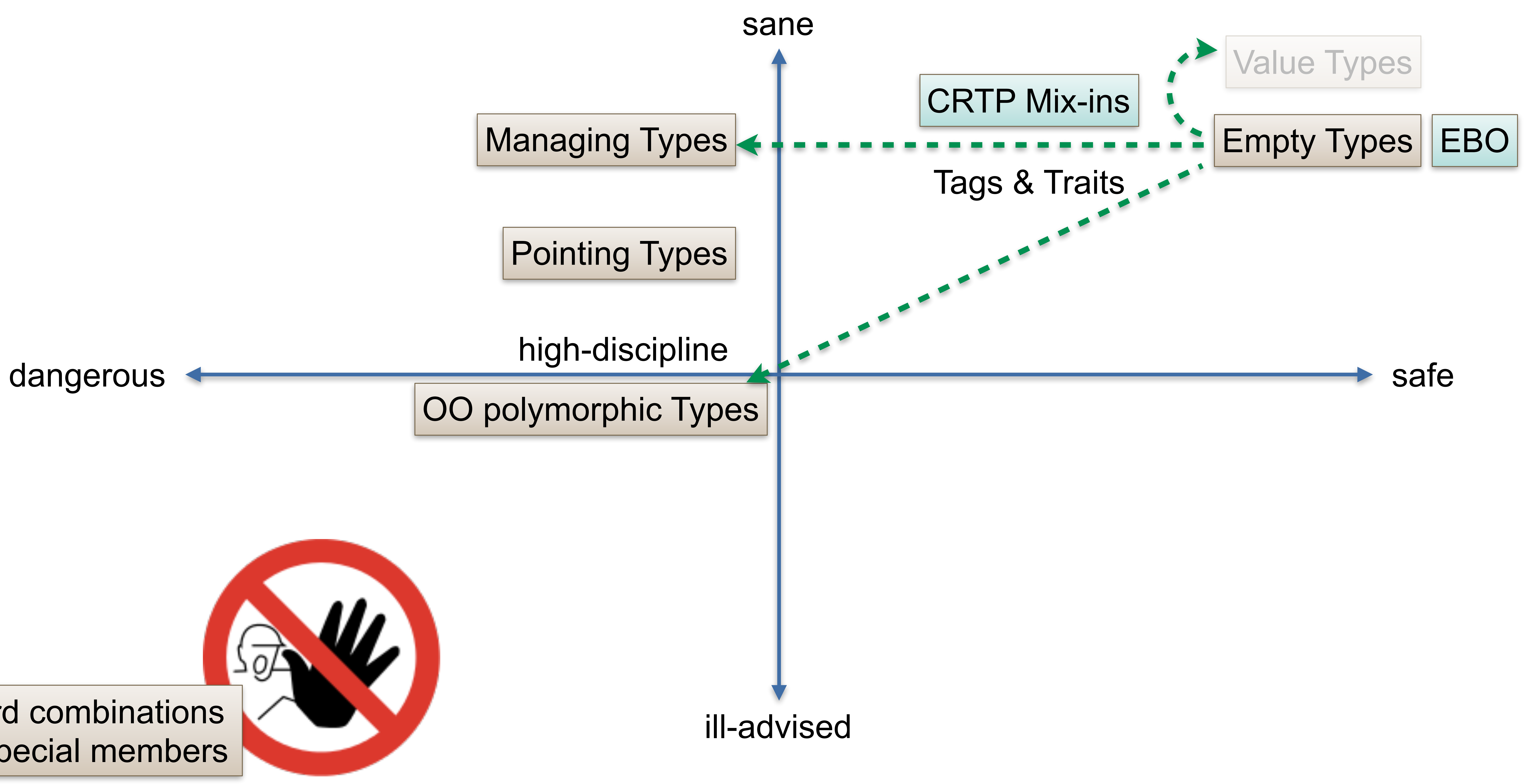
Empty Classes - useful?

"Oh you don't get something for nothing"
-- Rush

"Something for Nothting" -- Kevlin Henney, 1999

In C++ Empty Class you get something for nothing!

Dimensions Safety and Sanity…



Tag Types: Overload selection - sometimes with universally usable constants

- **Iterator Tags**
  - `input_iterator_tag, output_iterator_tag, forward_iterator_tag, bidirectional_iterator_tag, random_access_iterator_tag`
- **in place marker: `in_place_t`**
  - `std::in_place` global value

```
template< class... Args >
constexpr explicit
optional( std::in_place_t, Args&&... args );



// calls std::string( size_type count, CharT ch ) constructor
std::optional<std::string> o5(std::in_place, 3, 'A');
```

```
template< class BDIter >
void alg(BDIter, BDIter, std::bidirectional_iterator_tag)
{
    std::cout << "alg() called for bidirectional iterator\n";
}
template <class RAIter>
void alg(RAIter, RAIter, std::random_access_iterator_tag)
{
    std::cout << "alg() called for random-access iterator\n";
}
template< class Iter >
void alg(Iter first, Iter last)
{
    alg(first, last,
        typename std::iterator_traits<Iter>::iterator_category());
}
int main()
{
    std::vector<int> v;
    alg(v.begin(), v.end());

    std::list<int> l;
    alg(l.begin(), l.end());

//    std::istreambuf_iterator<char> i1(std::cin), i2;
//    alg(i1, i2); // compile error: no matching function for call
}
```

- `nullptr_t` and `nullptr` are similar but built-in

- **represent values as types**
  - integral_constant<T,T v>
    - true_type, false_type
  - ratio<5,3>
  - integer_sequence<T, T...vs>
- **What for?**
- **SFINAE**
  - template specialization selection
  - overload selection
- **Periods/scale in duration (ratio)**
- **tuple element access (integer_sequence)**

```
template<class T, T v>
struct integral_constant {
    using value_type=T;
    static constexpr value_type value = v;
    using type=integral_constant; // injected-class-name
    constexpr operator value_type() const noexcept {
        return value; }
    constexpr value_type operator()() const noexcept {
        return value; }
};
using true_type=integral_constant<bool,true>;

static_assert(integral_constant<bool,true>::value,"");
static_assert(true_type::value,"member access");
static_assert(true_type{},"auto-conversion");
static_assert(true_type{}(),"call operator");
static_assert(std::is_same_v<true_type, true_type::type>,
     "type meta");
```

Empty class speciality: EBO Empty Baseclass Optimization

- **a class without members has at least size 1**
- **but not if it is used as a base class**
  - unless the derived type starts with a member of the same type
- **Often used to optimize away size**
  - see uniqe_ptr with default_delete or with my suggested default_free class instead of using a function pointer for free
  - also good for (CRTP-)Mix In classes, so they do not enlarge the object unnecessarily
- **C++20 adds that possibility even for "empty" members**
  - `[[no_unique_address]]` attribute

```
struct empty{};
static_assert(sizeof(empty)>0,
  "there must be something");

struct plain{
  int x;
};
static_assert(sizeof(plain)==sizeof(int),
  "no additional overhead");

struct combined : plain, empty{
};
static_assert(sizeof(combined)==sizeof(plain),
  "empty base class should not add size");
```

- **a class without members has at least size 1**
- **but not if it is used as a base class**
  - unless the derived type starts with a member of the same type
  - each subobject of the same type must then have a unique address
- **For EBO to work nicely, have the first base hold the member(s) and further bases refer to it**
- **In addition use CRTP to ensure that each type differs**

```
struct empty{};
static_assert(sizeof(empty)>0
  && sizeof(empty)<sizeof(int),
  "there should be something");

struct ebo : empty{
  empty e;
  int i; // aligned to int
};
static_assert(sizeof(ebo)==2*sizeof(int),
  "ebo must not work");

struct noebo: empty{
  ebo e;
  int i;
};
static_assert(sizeof(noebo)==4*sizeof(int),
  "subojects must have unique addresses");
```

```cpp
template <typename V, typename TAG>
struct strong {
   using value_type=V;
   V val;
};

template <typename U>
struct Eq{
   friend constexpr bool
   operator==(U const &l, U const& r) noexcept {
      auto const &[vl]=l;
      auto const &[vr]=r;
      return {vl == vr};
   }
   friend constexpr bool
   operator!=(U const &l, U const& r) noexcept {
      return !(l==r);
   }
};
template <typename U>
struct Inc{
   friend constexpr auto operator++(U &rv) noexcept {
      auto &[val]=rv;
      ++val;
      return rv;
   }
   friend constexpr auto operator++(U &rv,int) noexcept {
      auto res=rv;
      ++rv;
      return res;
   }
};
template <typename U>
struct Out {
   friend std::ostream&
   operator<<(std::ostream &l, U const &r) {
      auto const &[v]=r;
      return l << v;
   }
};
template <typename U, template <typename ...> class ...BS>
struct ops:BS<U>...{};

struct WaitC:strong<unsigned,WaitC>
            ,ops<WaitC,Eq,Inc,Out>{};
static_assert(sizeof(unsigned)==sizeof(WaitC));
void testWaitCounter(){
   WaitC c{};
   WaitC const one{1};
   ASSERT_EQUAL(WaitC{0},c);
   ASSERT_EQUAL(one,++c);
   ASSERT_EQUAL(one,c++);
   ASSERT_EQUAL(3,c.val);
}
```

aggregate

structured bindings

CRTP and EBO Mixin

no overhead

"Empty" Adapters - possible, but requires discipline!

- **"invalid" inheritance, sometimes violating Liskov Substitution Principle**
  - but OK, if only extending or adapting functionality and never sliced to base class
  - inherits constructors from base - C++11 made those adapters much more practical
- **requires discipline in use, should never implicitly "downgraded" (upcasted)**
  - slicing harmful then, beware of use in code taking the base class type as parameter
  - If you use this to strengthen the invariant, e.g., a SortedVector inheriting from std::vector, very high discipline required, better wrap then!

```cpp
template<typename T, typename CMP=std::less<T>>
class indexableSet : public std::set<T,CMP>{
  using SetType=std::set<T,CMP>;
  using size_type=int;
public:
  using std::set<T,CMP>::set;

  T const & operator[](size_type index) const {
    return at(index);
  }
  T const & at(size_type index) const {
    if (index < 0) index += SetType::size();
    if (index < 0 || index >= SetType::size())
        throw std::out_of_range{"indexableSet:"};
    return *std::next(this->begin(),index);
  }
  T const & front() const {
    return at(0);
  }
  T const & back() const {
    return at(-1);
  }
};
```

"I just wanted to point to something"
Jonathan Müller (@foonathan), ACCU 2018

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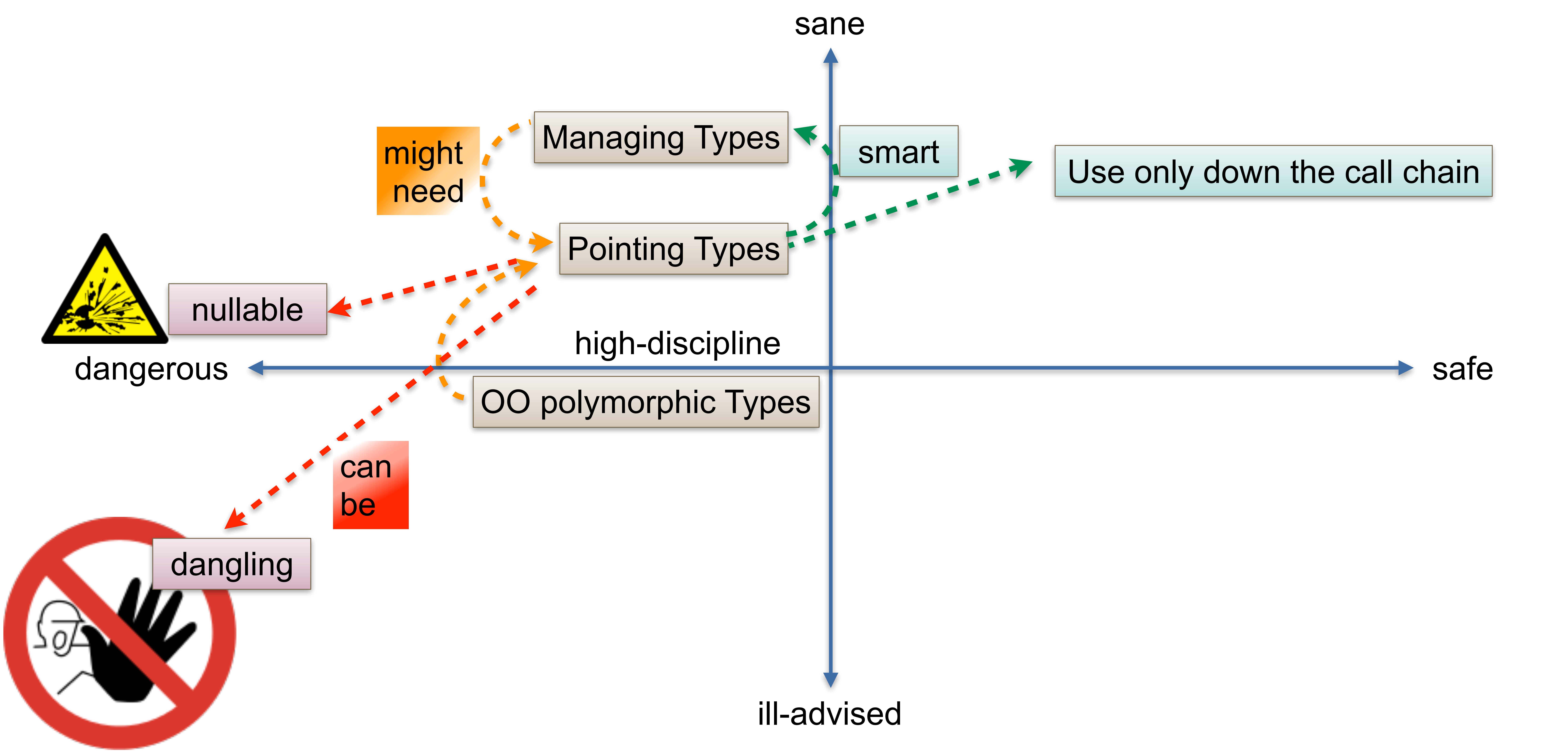
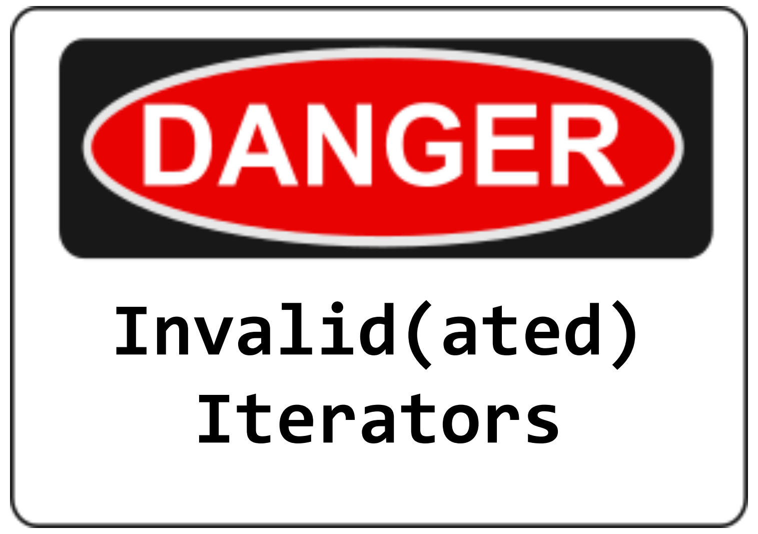
Dimensions Safety and Sanity… and "pointing" types



- **C++ allows to define types that refer to other objects**
- **This means life-/using-time of the referring object needs not to extend the lifetime of the referred**
- **While often Regular, those types are not Value Types**
  - they do not exist "out of time and space"

- **Iterators**
- **Smart Pointers**
- **Reference Wrapper**
- **Views and Spans**

- **Iterators satisfy concept Regular<T>, except for the need of DefaultConstructible**
  - istream(buf)_iterators have a special "eof" value, that is default constructed
- **Most iterators refer to other objects in containers**
  - relationship to the "pointed to" object as well as the container
  - changing the container can invalidate an iterator, but not always
  - dual role: reference to an object (e.g., find() result) and iteration



- **special iterator values (non-dereferencable):**
  - past the end-of-sequence iterator (end()) or before begin-of-sequence (forward_list::before_begin())
  - "singular" iterators (nullptr)
  - invalidated iterators due to changes in the container
  - Do not rely on iterator staying valid if a container's content can change

Usually invalid iterators can not be detected: UB

Special "pointer": std::reference_wrapper (non-null, non-owning, assignable, callable)

- **role: re-assignable lvalue (const) reference**
  - is not "nullable"! But can be dangling!
- **can be used for class members to keep class "regular"**
  - T& as a member disables assignment
- **can be used in container to refer to elements in other container**
  - use a container of (indices) into other container
- **automatically converts to reference**
  - or access via get()
- **wraps function references**
  - overloads operator()
- **Factory functions: std::ref(T&), std::cref(T const&)**

```
template <class T>
class reference_wrapper {
public:
  // types
  typedef T type;

  // construct/copy/destroy
  reference_wrapper(T& ref) noexcept : _ptr(std::addressof(ref)) {}
  reference_wrapper(T&&) = delete;
  reference_wrapper(const reference_wrapper&) noexcept = default;

  // assignment
  reference_wrapper& operator=(const reference_wrapper& x)
    noexcept = default;

  // access
  operator T& () const noexcept { return *_ptr; }
  T& get() const noexcept { return *_ptr; }

  template< class... ArgTypes >
  std::invoke_result_t<T&, ArgTypes...>
    operator() ( ArgTypes&&... args ) const {
    return std::invoke(get(), std::forward<ArgTypes>(args)...);
  }

private:
  T* _ptr;
};
```

Smart Pointers - more in the pipeline for standardization

- **observer_ptr<T>**
  - "borrows" object, does not own pointee
  - library fundamentals TS v2 (not std)
- **unique_ptr<T>**
  - owns pointee, cleans afterwards
- **shared_ptr<T>, weak_ptr<T>**
  - shared ownership
  - overhead for atomic counting
  - may "pseudo-leak", even when object is deleted

```
template <typename T>
using observer_ptr=T *;
```

My current recommendation:

- prefer unique_ptr<T> for heap-allocated objects
- for sharing keep unique_ptrs in a managing container and use references or reference_wrapper (some would say to use T* pointers)
- absolutely NO plain pointers with arithmetic (as in C)

Where should I use string_view? - also a "pointing" type

- **As a parameter type for functions that do not copy, save or change a string**
  - If read-only string processing is required
- **enables calling with C-style (char array) strings and std::string**
  - safer than (char const *)
  - better performance than (std::string const &)
  - beware of generic overloads when replacing existing APIs
    - might need overloads for all available character types (string_view, wstring_view) - no CharT deduction possible
    - I tried for the standard and failed!
- **In practice much less useful than I originally thought**
  - std::string pass-by-value often better when serious processing is required
- **Do never return std::string_view!**

- **Always define pointer variables const**
  - absolutely no pointer arithmetic!!!!!
  - especially for pointer parameters
- **Sidestep plain C-style pointers as much as possible**
- **Absolutely NO C-style arrays**
  - they degenerate to pointers and require pointer arithmetic!
  - even built-in operator[] is pointer arithmetic!

```
int demo(int *const pi){
  //*pi++;
  (*pi)++;
  return *pi;
}
```

```
void dont_demo(int *const pi){
  1[pi]=42;
  pi[0]=41;
}
void testDont(){
  std::array<int,2> a{};
  dont_demo(a.data());
  std::initializer_list<int> exp{41,42};
  ASSERT_EQUAL_RANGES(begin(exp),end(exp),begin(a),end(a));
}
```

What to do about it?

- **All "pointing" Types live in the "dangerous" quadrant**
- **High programmer discipline required**
- **Unfortunately code compiles**
  - often for backward compatibility
  - rules for iterator invalidation are subtle and rely on knowing implementation details
    - changing a container breaks code
    - Do not rely on iterator staying valid if a container's content can change
- **Ideas exist for static analysis (-> Herb Sutter)**
  - it is safe to pass them down the call chain
  - it is often unsafe to use them if you do not control the lifetime of the pointee

Referring stuff obtained from temporaries is dangerous

- **See my lightning talk on the problem with reverse adapter for range for**
  - init-statements with additional variable is just too ugly, IMHO
- **Just an idea (may be worth a ISO C++ paper?)**
  - provide deleted overloads for begin(), end() etc for rvalue references.
  - might break already wrong code
  - members returning elements by reference should return by value for temporaries

```
void testTemporaryArrayAccess(){
   ASSERT_EQUAL(2,(std::array{1,2,3}).at(1));
   int &i = std::array{2,3}[0];
   i=1; // UB
}
void testBeginTemporaryShouldNotCompile(){
   auto it = std::array{1,2,3}.begin();
   ASSERT_EQUAL(1,*it);
}
```

```
constexpr iterator
begin() & noexcept
{ return iterator(data()); }
constexpr const_iterator
begin() const & noexcept
{ return const_iterator(data()); }
constexpr iterator
begin() && noexcept  = delete;
```

```
constexpr reference
operator[](size_type __n)  & noexcept
{ return _AT_Type::_S_ref(_M_elems, __n); }
constexpr const_reference
operator[](size_type __n) const & noexcept
{ return _AT_Type::_S_ref(_M_elems, __n); }
constexpr value_type
operator[](size_type __n) && noexcept
{ return std::move(_M_elems[__n]); }
```

Managing stuff

"monomorphic object types"
-- Richard Corden, PRQA

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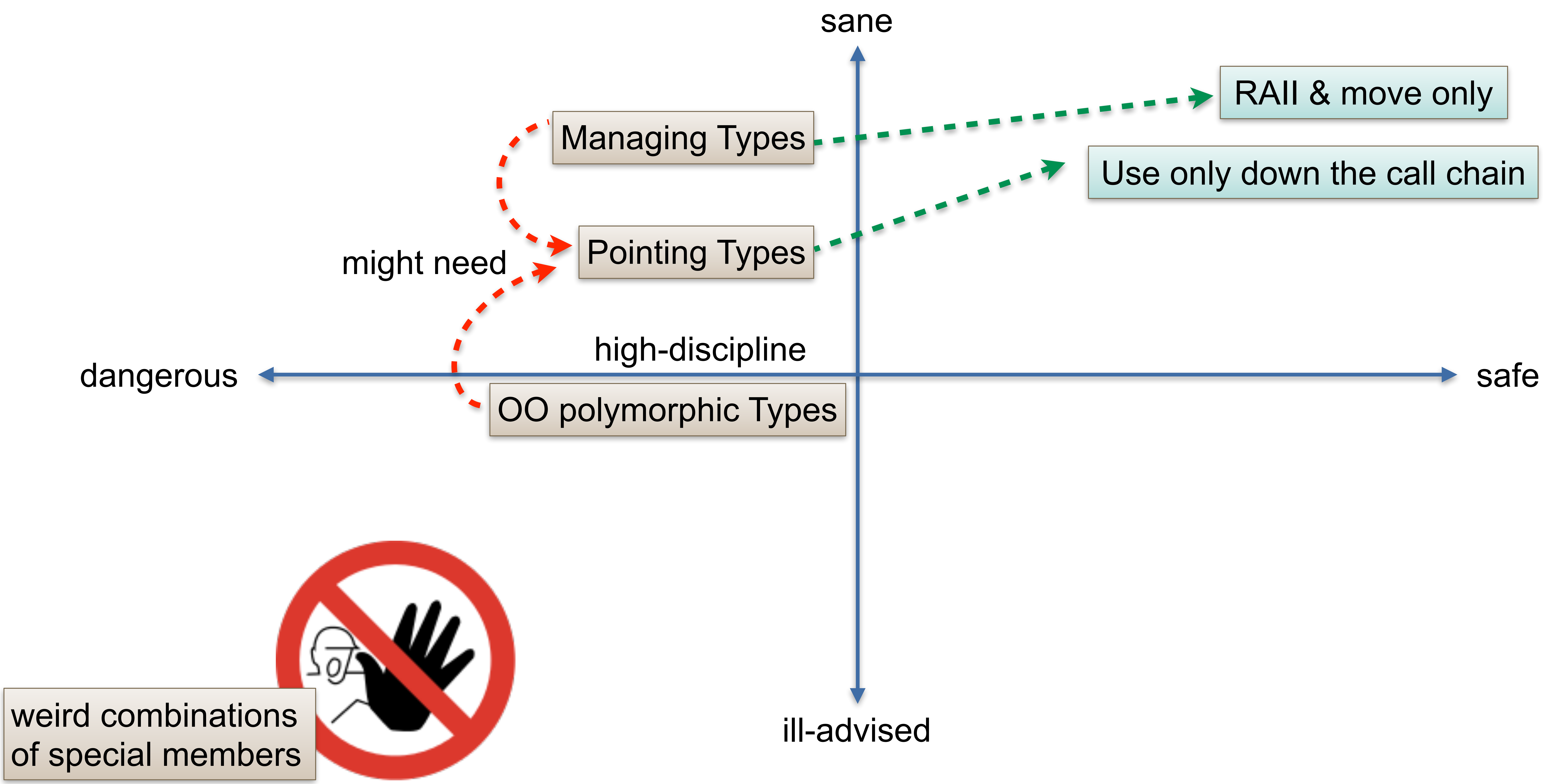


Manager Design Pattern: Monomorphic Object Types

- **Instances of monomorphic object types have significant identity (they are not values)**
- **Copying and assignment is prohibited**
  - Factories can still return by value from a temporary (C++17!)
  - implicitly or explicitly - non-Regular types
- **Passed by Reference (or Pointer-like type)**
  - "long" lifetime, allocated high-up the call hierarchy or on heap
- **No virtual members, no inheritance (except for mix-ins)**
- **Roles**
  - manage other objects, i.e., contain a container of something: vector<unique_ptr<T>> as member
  - wrap hardware or stateful I/O
  - encapsulate other stateful behavior, e.g., context of State design pattern, Builder, Context Object

```
struct ScreenItems{
  void add(widget w){
    content.push_back(std::move(w));
  }
  void draw_all(screen &out){
    for(auto &drawable:content){
      drawable->draw(out);
    }
  }
private:
  ScreenItems& operator=(ScreenItems &&) noexcept
     =delete; // all others deleted, except default
  widgets content{};
};
static_assert(!std::is_copy_constructible_v<ScreenItems>,"no copying");
static_assert(!std::is_move_constructible_v<ScreenItems>,"no moving");
ScreenItems makeScreenItems(){
  return ScreenItems {}; // must be a temporary
}
```

Use RAII (Resource Acquisition Is Initialization)

- **OK, make_unique() (**and make_shared) **for heap allocation.**
- **What else?**
- **Use std-library RAII classes, e.g., string, vector, fstream, ostringstream, thread, unique_lock**
- **Use boost-library RAII classes, if needed, e.g., boost.asio's tcp::iostream**

- **Don't write your own generic RAII!**
- **wait for C++20's std::unique_resource<T,D>: http://wg21.link/p0052**
  - You can use my github version with C++17
  - Ask me per email for a pre-C++17 implementation (or look for an old revision on my github)

Dynamic Polymorphism

"inheritance is the base class of Evil"
  -- Sean Parent, Adobe

Your C++ deserves it

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

INSTITUTE FOR SOFTWARE

Do you Remember: What Special Member Functions Do You Get?

What you get

What you write

	default constructor	destructor	copy constructor	copy assignment	move constructor	move assignment
nothing	defaulted	defaulted	defaulted	defaulted	defaulted	defaulted
any constructor	not declared	defaulted	defaulted	defaulted	defaulted	defaulted
default constructor	<u>user declared</u>	defaulted	defaulted	defaulted	defaulted	defaulted
destructor	defaulted	<u>user declared</u>	defaulted (!)	defaulted (!)	not declared	not declared
copy constructor	not declared	defaulted	<u>user declared</u>	defaulted (!)	not declared	not declared
copy assignment	defaulted	defaulted	defaulted (!)	<u>user declared</u>	not declared	not declared
move constructor	not declared	defaulted	deleted	deleted	<u>user declared</u>	not declared
move assignment	defaulted	defaulted	deleted	deleted	not declared	<u>user declared</u>

Howard Hinnant's Table: https://accu.org/content/conf2014/Howard_Hinnant_Accu_2014.pdf
Note: Getting the defaulted special members denoted with a (!) is a bug in the standard.

Making a OO base class T non-copyable: T& operator=(T&&) noexcept=delete;

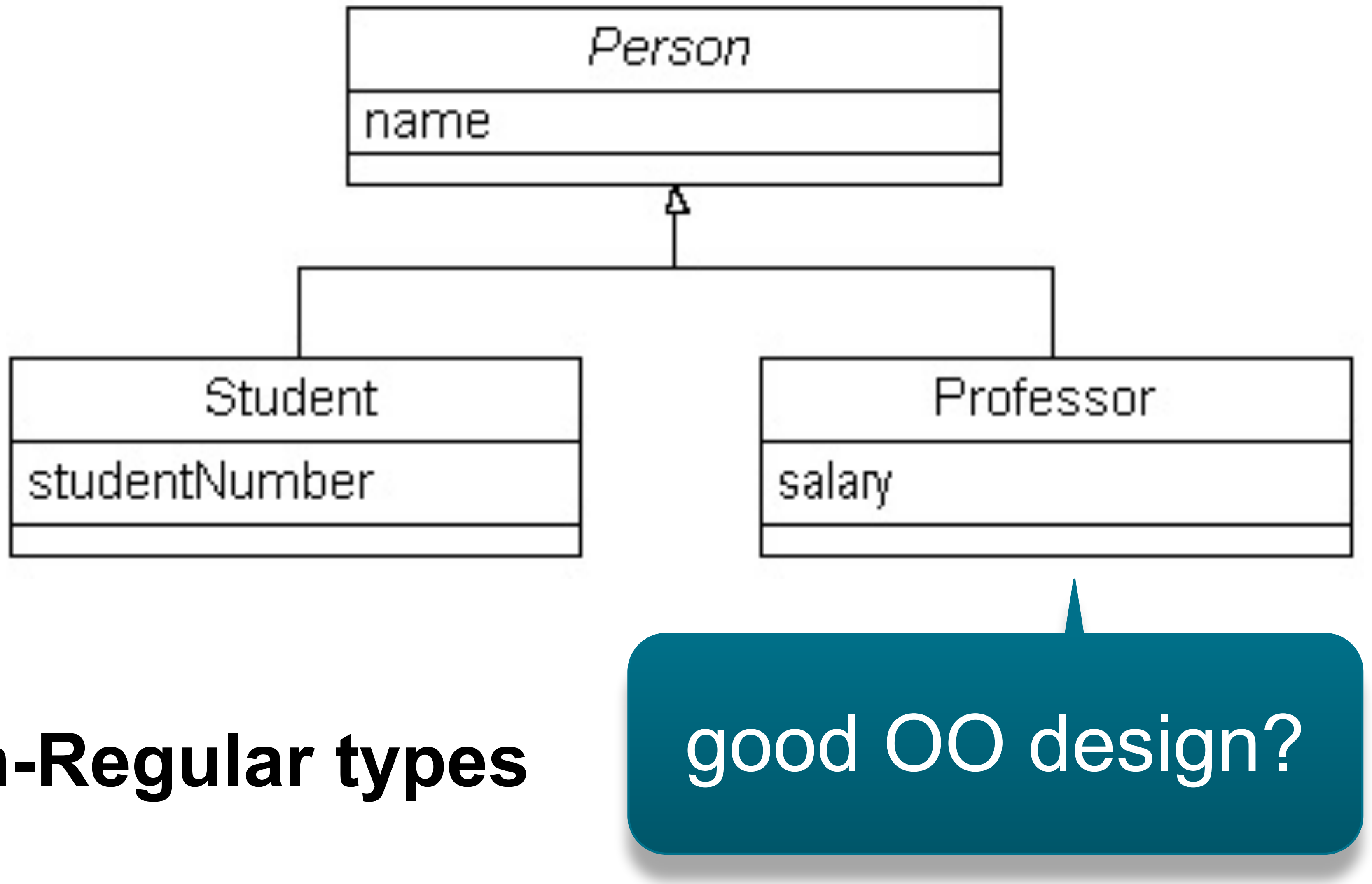
What you get

What you write

	default constructor	destructor	copy constructor	copy assignment	move constructor	move assignment
nothing	defaulted	defaulted	defaulted	defaulted	defaulted	defaulted
any constructor	not declared	defaulted	defaulted	defaulted	defaulted	defaulted
default constructor	user declared	defaulted	defaulted	defaulted	defaulted	defaulted
destructor	defaulted	user declared	defaulted (!)	defaulted (!)	not declared	not declared
copy constructor	not declared	defaulted	user declared	defaulted (!)	not declared	not declared
copy assignment	defaulted	defaulted	defaulted (!)	user declared	not declared	not declared
move constructor	not declared	defaulted	deleted	deleted	user declared	not declared
move assignment	defaulted	defaulted	deleted	deleted	not declared	user declared

Howard Hinnant's Table: https://accu.org/content/conf2014/Howard_Hinnant_Accu_2014.pdf
Note: Getting the defaulted special members denoted with a (!) is a bug in the standard.

Polymorphic Object Types -- think thrice about using virtual!

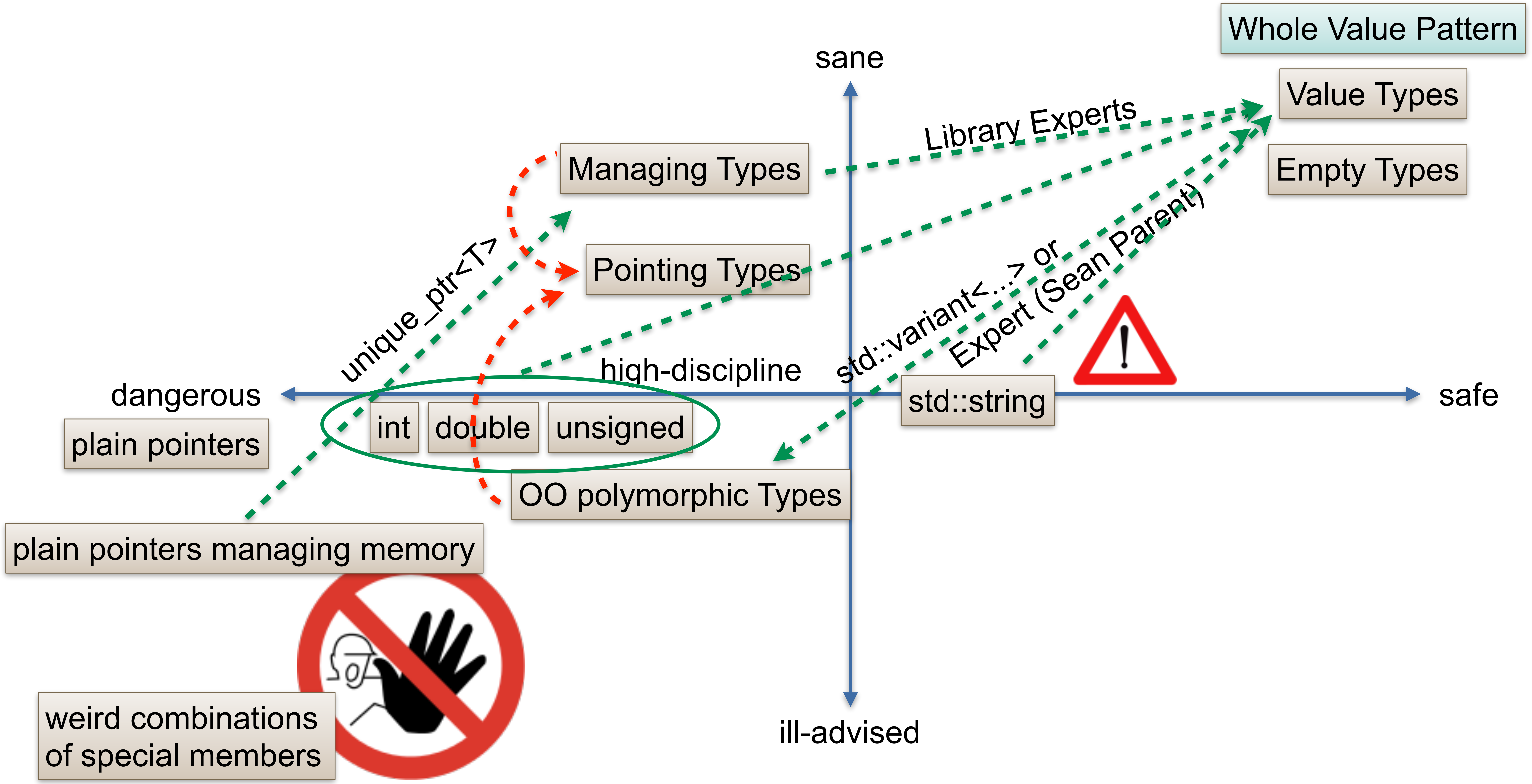


- **Base in class in hierarchy defines abstraction**
  - usually abstract (pure virtual destructor)
- **Instances of polymorphic object types have important identity**
- **Copying and assignment is prohibited (implicitly or explicitly) - non-Regular types**
- **Passed by Reference (or Pointer-like type)**
  - "long" lifetime, allocated up in the call hierarchy (best) or on the heap (doable)
- **Virtual member functions and (pure) virtual destructor in base class**
  - subclasses should not add additional virtual members, define pure virtual destructor of base
- Most other attempts with multiple layers of inheritance or even multiple inheritance are often futile

Sane and less sane combinations

	Some constructor	default constructor	destructor	copy constructor	copy assignment	move constructor	move assignment
Aggregates	none	defaulted	defaulted	defaulted	defaulted	defaulted	defaulted
Simple Values	yes	none / =default	defaulted	defaulted	defaulted	defaulted	defaulted
Manager	typical	none / =default	Expert Level - =default	=delete	=delete	=default/ =delete	=default/ =delete
RAII	yes	none / =default	user declared	=delete	=delete	=default/ =delete	=default/ =delete
OO - Base	may be	may be	=default virtual!	=delete	=delete	=delete	=delete
Manager & Value	typical	resurrected	Expert Level - =default	Expert Level Implementation	Expert Level Implementation	Expert Level Implementation	Expert Level Implementation
OO & Value Sean Parent			Expert Level - =default	Expert Level Implementation	Expert Level Implementation	Expert Level Implementation	Expert Level Implementation

Dimensions Safety and Sanity…



Take aways 🍔 🍟

- **Learn to appreciate the C++ Type System - every cast is an indication to think & refactor!**
- **Model with Value Types almost always**
  - but be aware of the **relative vs. absolute** dimension problem in your units!
- **Wrap primitives using Whole Value, even a named simple struct communicates better than** int
- **Be aware of the required expertise and discipline for Manager types and OO hierarchies**
  - especially when combining them
- **Be very disciplined about using Pointing types, this includes references and string_view**
- **Run away from types with weird special member function combinations, even if defaulted**
  - usually they attempt to do too much or the wrong thing