Working with Types

Lecture 8

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https://teaching.hkaiser.org/spring2024/csc3380/

Software Development Notes

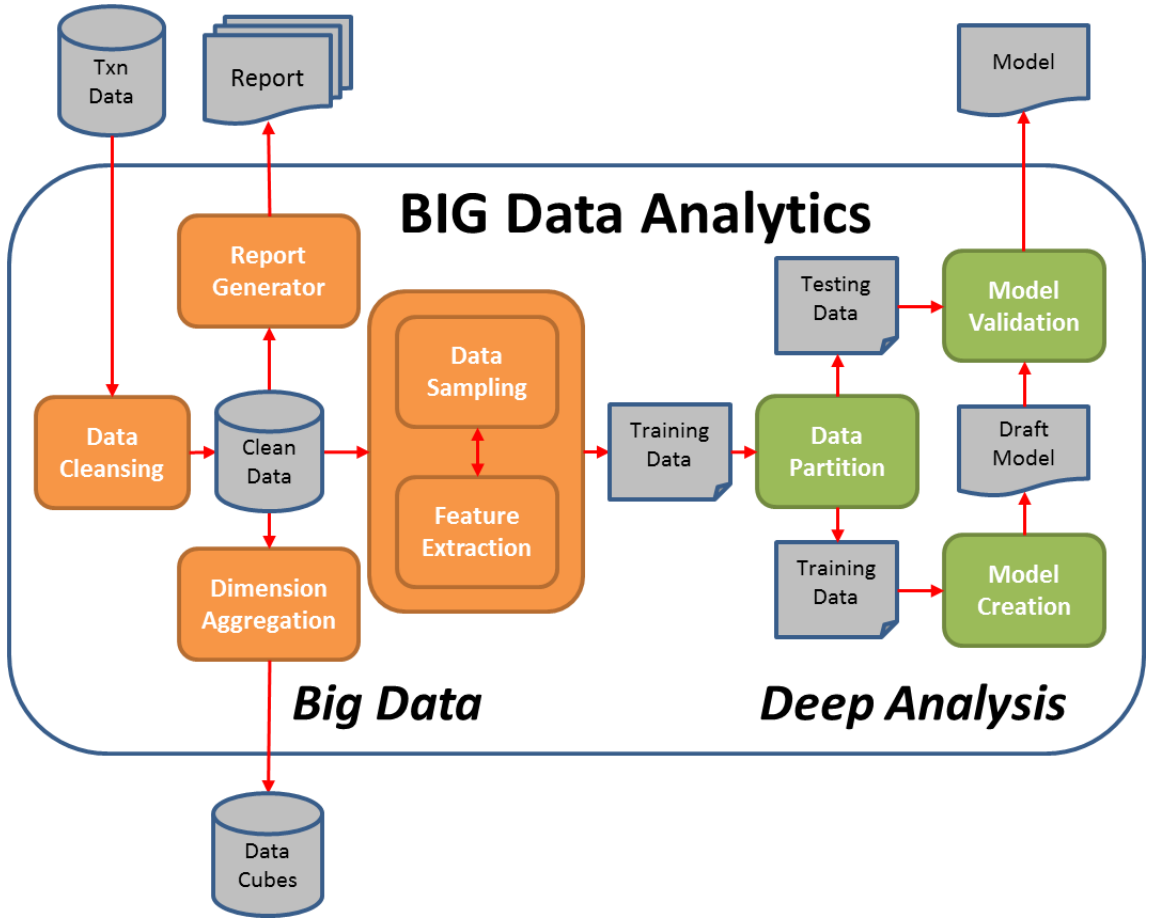
Software Architecture

- Software system architecture is the overall shared vision of the software system
  - The high level design of a software system
- The fundamental organization of a system, embodied in its major components
  - Each component represents a broad category of functionality
  - Components represent possibly many classes that work together as one
- Their relationships to each other and the environment
  - Components are linked with connections
  - Each connection represents potentially numerous communication channels
- The principles governing its design and evolution

Important Properties of Software Architecture

- High-enough level of abstraction that the system can be viewed as a whole
- Structure must support the functionality required of the system
- Structure must conform to the system qualities (e.g. performance, security, reliability, flexibility, and extensibility)
- At the architectural level, all implementation details are hidden
- Keep your architecture as small as it possibly can be, while still meeting your architectural objectives

Software System Architecture Example



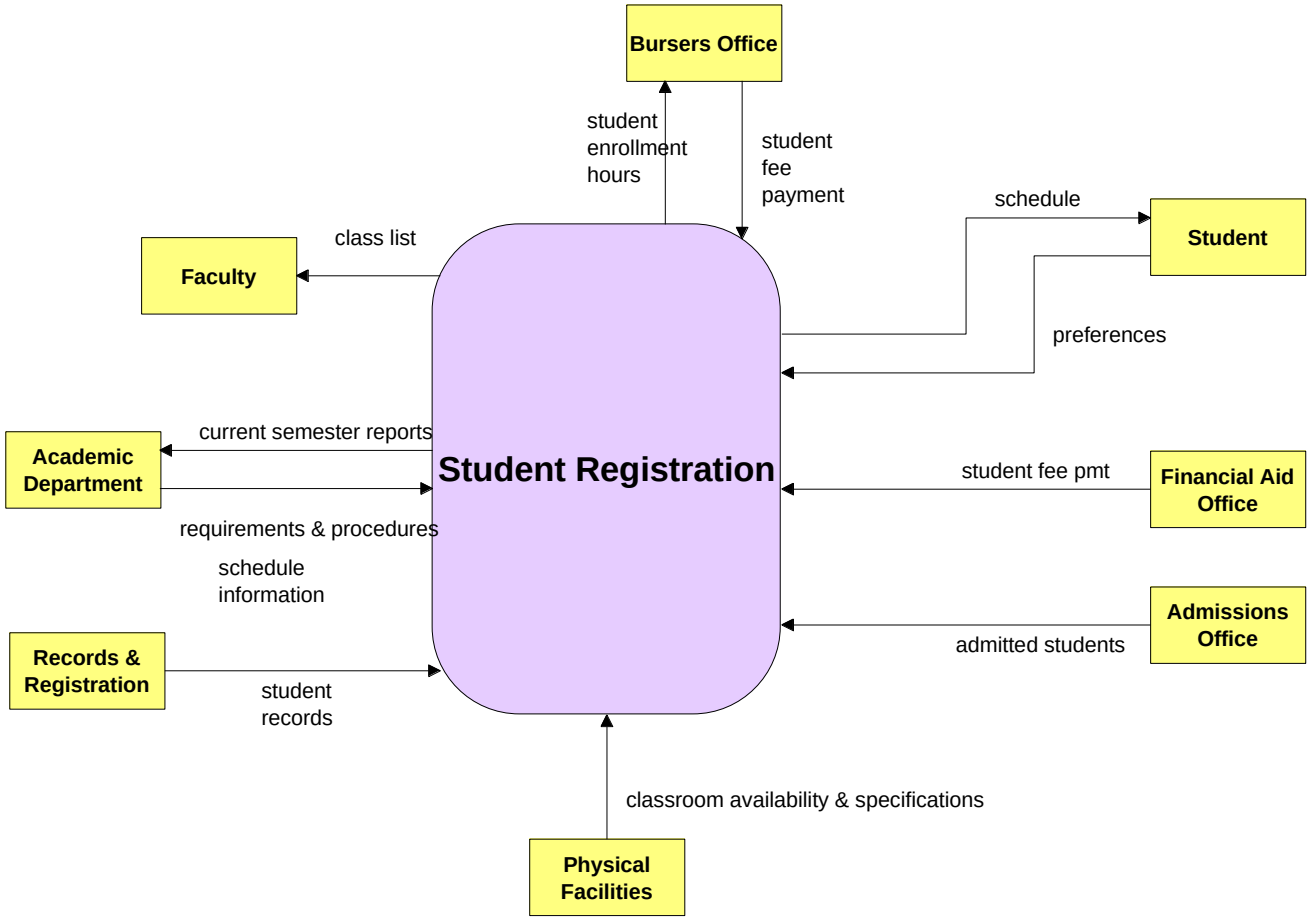
- Best Practice: Approximately 7 components (± 2)
- Curved rectangles represent components
- Like-colored components represent coupled components
- Cylinders represent data repositories (usually databases)
- Waved bottom rectangles represent files
- Dog-eared rectangles represent data sets or files
- Arcs indicate direction of data flow

http://horicky.blogspot.com/2012/08/big-data-analytics.html

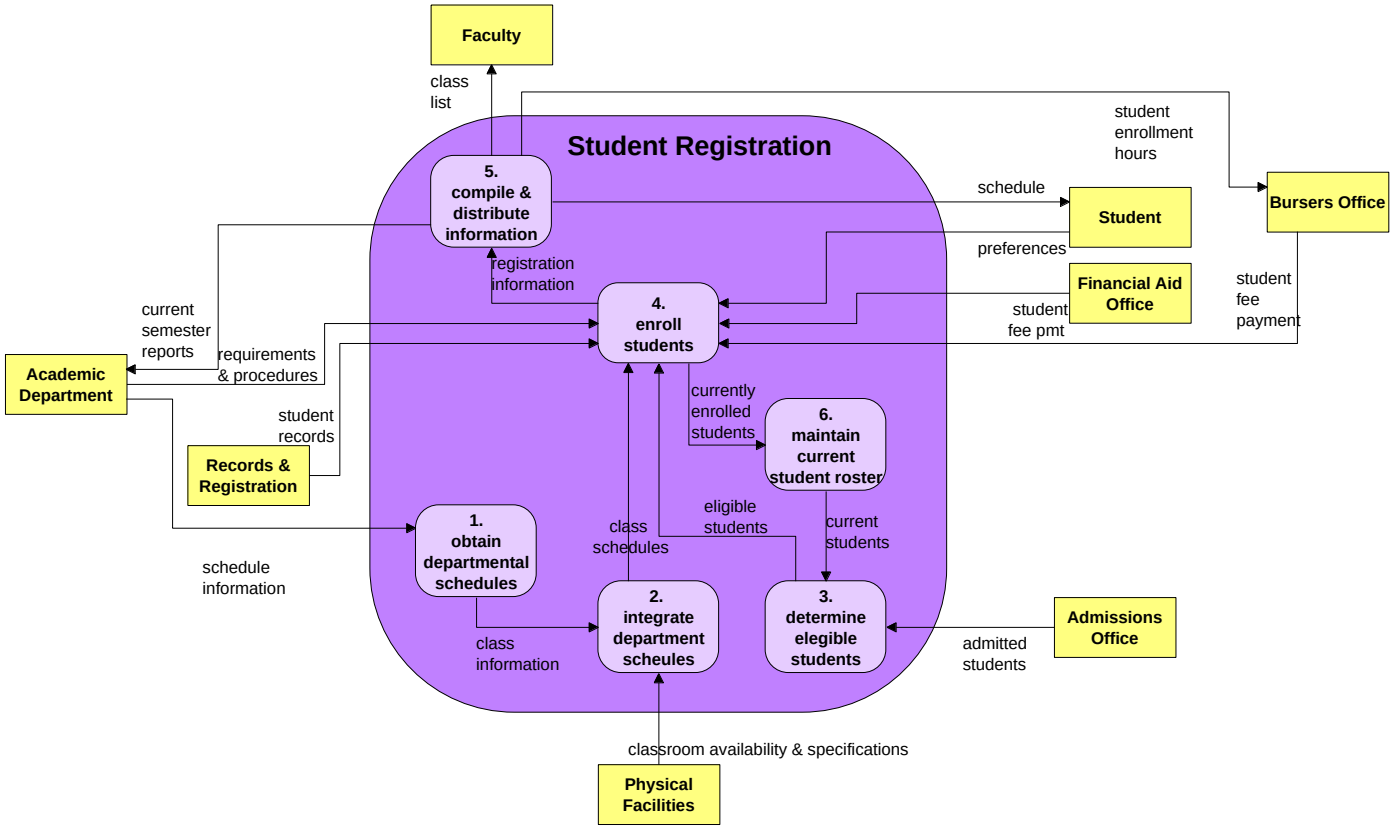
Data Flow Diagrams

- Start with the Architecture Diagram
- Add data that is exchanged between components to all diagram edges
- Refine diagrams sufficiently to hand off to development team
  - Level 0
    - Software system is a black box
    - Data flow is between software system and external entities
  - Level 1
    - Software System Architecture Diagram
    - Add data flow between system components
  - Level 2
    - Component Design Diagrams
    - Add data flow between subcomponents
  - etc.

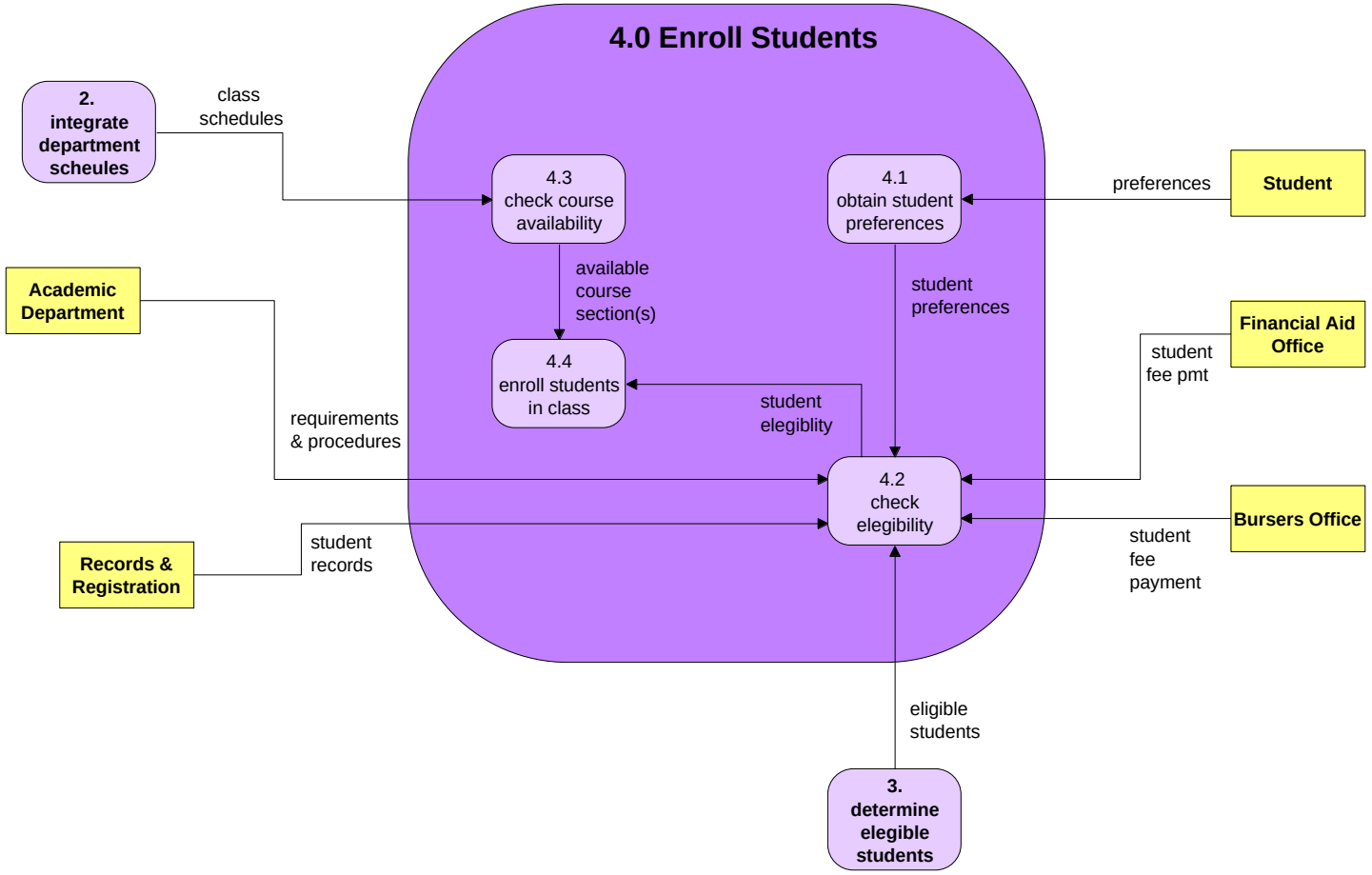
Data Flow Diagram Example: Level 0



Data Flow Diagram Example: Level 1



Data Flow Diagram Example: Level 2



What is a Type?

Abstract

- What are types? What are objects?
- A pattern for regular types: `singleton`
  - Semi-regular `singleton`
  - Regular `singleton`
  - Totally ordered `singleton`
- Another useful regular type: `instrumented`

What is a 'type'?

- A 'type' (of an object) defines the following things:
  - The amount of memory required to store all the data that is needed to support the operations valid for a type
  - The rules of how to interpret the bits in that memory as values in order to be able to make sense of the bit-salad
  - The set of values that are valid
  - The set of operations that are valid on those values
- Examples of types:
  - `int`, `double`, `float` (built-in types)
  - `token`, `token_stream`, `std::vector`, etc. (user-defined types)

What is an 'object'?

- An object is an instance of a type
  - Occupies memory
  - Has an optional name (is a variable)
  - Has a lifetime
- Objects in C++ don't change their type
  - C++ is a type-safe language
  - C++ checks types and type compatibility at compile time
- Examples of objects:
  - `int i = 0;`
  - `token t('+');`
  - `std::vector<int> v = {1, 2, 3, 4, 5};`

Type Regularity

Regular Types

- Let's informally define what it means for a type to be 'Regular'
  - It behaves like an `int` (or any other built-in type)
- Regularity defines a set of properties a type should have
- Understanding regularity is important as it will allow us to understand what algorithms are allowed to do
  - Use only operations allowed for regular types
- Regular types are those that can be stored in standard containers (like `std::vector<T>`)
  - What properties must `T` have to be regular?
  - IOW, what properties must `T` have in order for it to be stored in a `std::vector<T>`
- We should be able to rely on `std::vector<T>` being regular if `T` is regular
- We will use **concepts** to describe those properties

Semiregular Types: Copy constructor

- `Semiregular` is a bit weaker than `Regular`
- We should be able to write:
  - Copy constructor (*initializes* `a`)
    - `T a(b);`
    - `T a = b;`
  - Both are equivalent, even the same, if `b` is of type `T`
- What are the semantics of this operation?
  - After this operation `a` should be equivalent to `b`
- What is equivalence?
  - A relation `R(a, b) = true` is equivalence, if it satisfies
    - symmetric: `R(a, b) <=> R(b, a)`
    - reflexive: `R(a, a)`
    - transitive: `R(a, b)` and `R(b, c) => R(a, c)`

Semiregular Types

- We actually want something way stronger. We want *equality*
- A copy is something which is *equal to the original, but not identical to it*
  - After `a` is copy constructed from `b` then `a == b`, whatever the meaning of equality
  - After `a` is copy constructed from `b` they have distinct identity markers.
    - In C++ the identity marker is usually the object's address: `&a != &b` (location in memory)
- All copy constructors must behave this way.
  - If somebody clever comes and says, "oh we're going to have semantics where we're going to have this shared thing".
  - Will it work? No. Copy has to construct a different thing.

Semiregular Types: Assignment

- Assignment operator:
  - `T a; a = b;`
- Construction (initialization) and assignment must be equivalent (lead to the same results):
  - `T a(b) <=> T a; a = b;`
- *Initialization* creates an initial state for a new object
- *Assignment* first cleans up old state of an existing object and then initializes its new state
- In order for these operations to have correct semantics, the types involved have to have *equality* defined (`operator==()`)
  - How would you know otherwise if two instances are equal?

Semiregular Types: Destructor

- Even if you don't call destructors directly (the compiler does, though):
  - `~T();`
- Ends the lifetime of an object

Regular Types

- The concept `Regular` extends `Semiregular` with equality operators which are `==` and `!=`
- We should define `==` so that after constructing a copy, the original and the copy are equal
- `!=` should always behave like: `!(a == b)`
- Fundamentally equal is a symmetric function. It compares two things
  - We will implement it as a `friend` function, not as a member function

Total orderings

- The concept `TotallyOrdered` extends `Regular` by adding a comparison operator `<`
- operator `<` must obey the following mathematical properties:
  - Axiom 1: Anti-reflexive: `!(a < a)`
  - Axiom 2: Transitive: If `a < b` and `b < c` then `a < c`
  - Axiom 3: Anti-symmetric: If `a < b` then `!(b < a)`
  - Axiom 4: If `a != b` then `a < b` or `b > a`
- The semantics of `<` must be totally bound to the semantics of equality and related operations
  - The following should always be true, otherwise the world perishes.
    - `a >= b  --> !(a < b)`
    - `a > b  --> b < a`
    - `a <= b  --> !(b < a)`

Singleton

A Pattern for Regular Types

- We'll develop the simplest possible Regular (even totally ordered) type: `singleton`
- The dictionary says: `singleton`, `pair`, `triple`, `quadruple`, etc.
  - A pair has two things, well a singleton has just one thing
- Can be used as a pattern (or "template") for any types you will want to create
  - It is the most simple class possible
    - It will have no (functionality oriented) code whatsoever
  - It is the most complete class possible
    - It will have all the language details about type creation that you need to know
  - It is a 'pure' regular type

Template type functions

- Singleton:

```
template <typename T>
struct singleton
{
    T value;
};
```

- `template <typename T>`
  - Why `template`?
    - We want to write something which takes one type and returns another type, i.e. a 'type function'
    - In C++ the `template` mechanism is just that
- Simplest type function example
  - `int*`: i.e. get an `int` and return an `int*`
  - Transform one type into another type
- Singleton is a type function that takes a `T` and gives us a `singleton<T>`

Compiler Generated Functions

- In C++, each user defined type has 6 special functions
  - Those are being generated by the compiler, if not explicitly provided
  - These functions are *always* available
- Here are the 6 functions
  - Default constructor
  - Destructor
  - Copy constructor
  - Copy assignment
  - Move constructor
  - Move assignment
- The special functions are being automatically used in certain situations

Compiler Generated Functions

- Constructors are automatically used whenever a new instance of a user defined type is created (start lifetime of object)
  - Default constructor is used when no additional arguments are supplied:

```
singleton<int> s;
```

  - Destructor is automatically called whenever an instance of a user defined type goes out of scope (ends the lifetime of an object)
  - Copy constructor is used whenever a new instance of a user defined type is created and initialized from another instance:

```
singleton<int> s1 = s;
```

  - Copy assignment is used whenever an existing instance of a user defined type is assigned to another instance:

```
singleton<int> s2; s2 = s1;
```

Compiler Generated Functions

- Any compiler generated special function by default invokes the corresponding special functions for all member data of the user defined type
  - Default constructor invokes default constructor of all members (in order of their definition)
  - Destructor invokes destructors of all members (in reverse order)
  - Etc.

Semi-regular `singleton`

- Let's implement support to make singleton Semiregular

```
// Semiregular:
singleton() {}     // default constructor: could be implicitly declared sometimes
~singleton() {}    // destructor: could be implicitly declared

singleton(singleton const& x) // copy constructor: could be implicitly declared
  : value(x.value)
{
}

singleton& operator=(singleton const& x) // copy assignment operator: could be implicitly declared
{
    value = x.value;
    return *this;
}
```

Semi-regular `singleton`

- Let's implement support to make singleton Semiregular

```
// Semiregular:

singleton() = default;          // default constructor
~singleton() = default;         // destructor


// copy constructor
singleton(singleton const& x) = default;

// copy assignment
singleton& operator=(singleton const& x) = default;
```

Semi-regular `singleton`

- What are the semantics of the default constructor?
  - In this case you want whatever the default value of `T` is, to be constructed. The compiler will do this for us.
- The default constructor will always be synthesized by the compiler unless you have another constructor.
  - Always add it to avoid surprises!

Semi-regular `singleton`

- Should the destructor be virtual?
  - No! Why should it be?
  - Some people say 'all destructors have to be virtual' – they couldn't be more wrong than that!
- Feel free to make singleton `final` to prevent people from deriving from it
  - There is no point in ever deriving from it anyways:

```
template <typename T>
struct singleton final
{
    // ...
};
```

Regular `singleton`

```
// Regular
friend bool operator==(singleton const& x, singleton const& y)
{
    return x.value == y.value;
}
friend bool operator!=(singleton const& x, singleton const& y)
{
    return !(x == y);
}
```

- Recall that we decided not to define these as member functions
  - they are symmetric
  - `friend` functions inside the class declaration are not member functions
    - but still have all the access to all the members
  - More importantly this signature is nice. If you put it outside you discover you have to write an ugly thing

Equality and the three laws of thought

- **The law of identity**: `a == a`
  - Popeye the Sailor used to say, "I am, what I am"
- **The law of non-contradiction**:
  - You cannot have a predicate `P` be true and `!P` be true at the same time.
- **The law of excluded middle**:
  - Every predicate `P` must be either true, or false.

Exercise: Figure out a type that violates the law of identity

Totally ordered `singleton`

```
// TotallyOrdered
friend bool operator<(singleton const& x, singleton const& y)
{
    return x.value < y.value;
}
friend bool operator>(singleton const& x, singleton const& y)
{
    return y < x;
}
friend bool operator<=(singleton const& x, singleton const& y)
{
    return !(y < x);
}
friend bool operator>=(singleton const& x, singleton const& y)
{
    return !(x < y);
}
```

Concepts in C++

- What requirements do we have apply to T in order for singleton<T> to be valid?
  - C++20 introduced concepts allowing to constrain use of singleton

```
template <typename T>
  requires(std::regular<T> || std::semiregular<T> || std::totally_ordered<T>)
struct singleton final
{
    // ...
};
```

Exercise: Copy the file for `singleton` and modify it to write `pair`

- You might wonder how == will work, if you plug-in only a semiregular type T
  - In C++ templates, things don't have to be defined unless they are used
    - If `T` has no equality, `singleton<T>` will have copy constructor and assignment but no equality.
    - If `T` has an equality, then `singleton<T>` will have equality
    - Etc.

Pattern: Composite

- **Context:**
  - 1. Primitive objects can be combined into composite objects
  - 2. Programs treat a composite object as a primitive object
- **Solution:**
  - 1. Define an interface that is an abstraction for the primitive objects
  - 2. A composite object contains a collection of primitive objects
  - 3. Both primitive classes and composite classes implement that interface
  - 4. When implementing a method from the interface, the composite class applies the method to its primitive objects and combines the results

Instrumented

A performance measuring tool

`instrumented<T>`

- We will write a wrapper (adapter, decorator) class `instrumented<T>` which will take a type `T` and behave exactly like `T`
- We will be able to use `instrumented<T>` for any algorithm or container
  - It will behave normally, just like a `T`
  - In addition it will count all the operations that are applied to it
- Which operations should we count?
  - The ones specified by our concepts!
- `T` will be `SemiRegular`, `Regular`, or `TotallyOrdered`
  - Redefine all the operations: copy constructor, assignment, operator<, etc, adding code to count them

instrumented<T>

- For example:

```
std::vector<double> vec;
my_func(vec.begin(), vec.end());
```

- Could be replaced by:

```
std::vector<instrumented<double>> vec;
my_func(vec.begin(), vec.end());
```

- And it will count all operations
- Writing this particular class will teach to write `Regular` classes right.

instrumented<T>

- What to do with all the counts? Where do they get stored?
- We will define a base class to hold this data:

```
struct instrumented_base
{
    enum operations {
        n = 0, copy, assignment, destructor, default_constructor,
        equality, comparison, construction
    };

    static constexpr size_t number_ops = 8;
    static constexpr char const* counter_names[number_ops] = {
        "n", "copy", "assignment", "destructor", "default_constructor",
        "equality", "comparison", "construction"
    };
    static double counts[number_ops];
};
```

instrumented<T>

- Use this base class as:

```
template <typename T>
    requires(std::semiregular<T> || std::regular<T> || std::totally_ordered<T>)
struct instrumented : instrumented_base
{
    // ...
};
```

- Note that the base class does not change the size of `instrumented<T>`, i.e.

```
sizeof(instrumented<T>) == sizeof(T)
```

instrumented<T>

- Copy and paste the singleton.hpp file we created
- Replace the string `singleton` with `instrumented`
- In addition to existing operations, we'll add counting, e.g.:

```
instrumented(instrumented const& x)    // copy constructor
  : value(x.value)
{
    ++counts[copy];                    // 'copy' is a constant index
}


instrumented()                         // default constructor
{
    ++counts[default_constructor];     // 'default_constructor' is another constant index
}
```

Pattern: Decorator

- **Context:**
  - 1. You want to enhance the behavior of a class. We'll call it the component class
  - 2. A decorated component can be used in the same way as a plain component.
  - 3. The component class does not want to take on the responsibility of the decoration.
  - 4. There may be an open-ended set of possible decorations.
- **Solution:**
  - 1. Define an interface that is an abstraction for the component
  - 2. Concrete component classes implement this interface
  - 3. Decorator classes also implement this interface
  - 4. A decorator object manages the component object that it decorates
  - 5. When implementing a method from the component interface, the decorator class applies the method to the decorated component and combines the result with the effect of the decoration.

Number of unique elements

- Counting operations and measuring execution time:
  - Using `std::set`

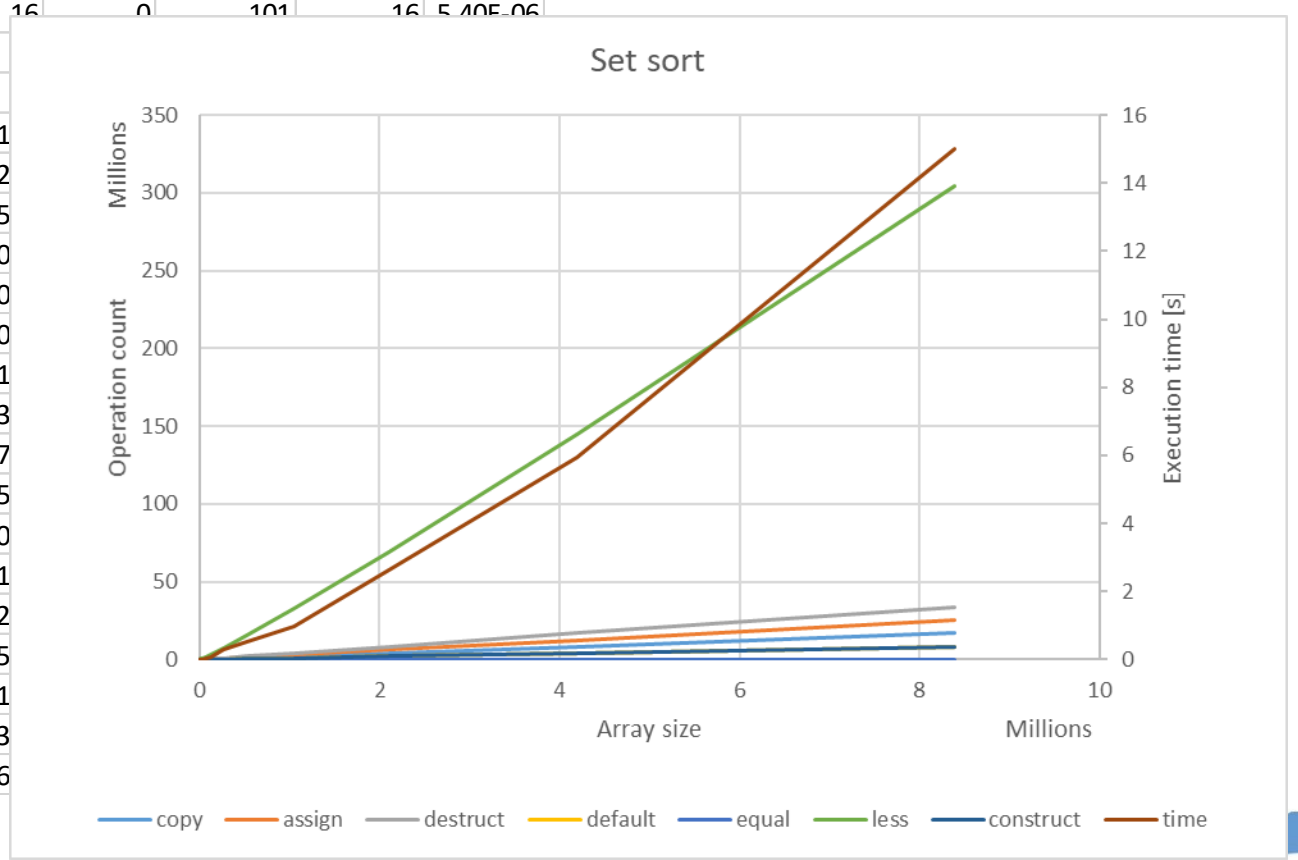
```
std::vector<instrumented<int>> v = {...};

std::set<instrumented<int>> set_of_ints(v.begin(), v.end());
std::cout << set_of_ints.size() << std::endl;
```

  - Using `std::sort` and `std::unique`:

```
std::sort(v.begin(), v.end());
std::cout << std::unique(v.begin(), v.end()) - v.begin() << std::endl;
```

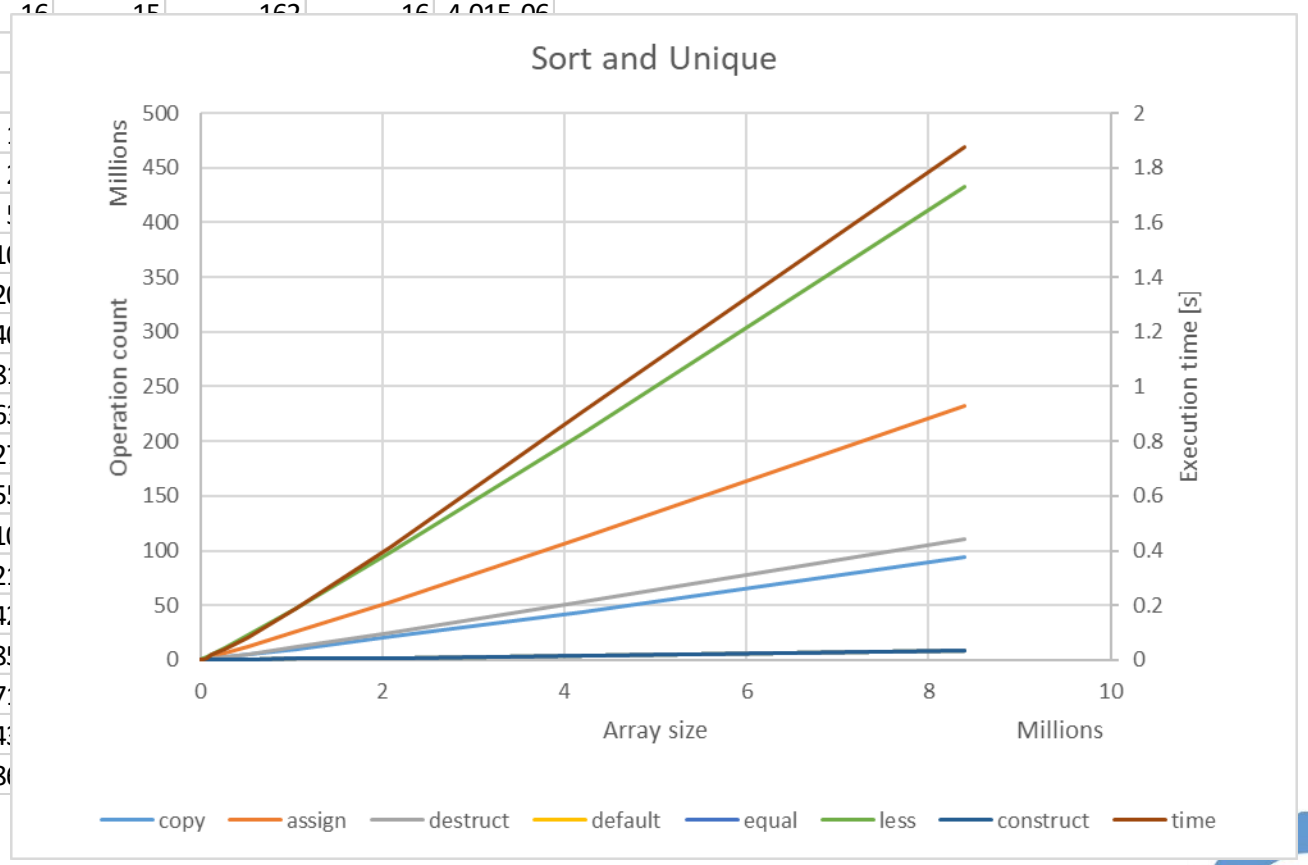
Using `std::set`

n	copy	assign	destruct	default	equal	less	construct	time
16	30	44	62	16	0	101	16	5.40E-06
32	57	82	121					
64	123	182	251					
128	252	376	508	1				
256	506	756	1018	2				
512	1021	1530	2045	5				
1024	2038	3052	4086	10				
2048	4090	6132	8186	20				
4096	8181	12266	16373	40				
8192	16375	24558	32759	81				
16384	32756	49128	65524	163				
32768	65522	98276	131058	327				
65536	131061	196586	262133	655				
131072	262130	393188	524274	1310				
262144	524283	786422	1048571	2621				
524288	1048560	1572832	2097136	5242				
1048576	2097134	3145692	4194286	10485				
2097152	4194292	6291432	8388596	20971				
4194304	8388590	12582876	16777198	41943				
8388608	16777197	25165786	33554413	83886				

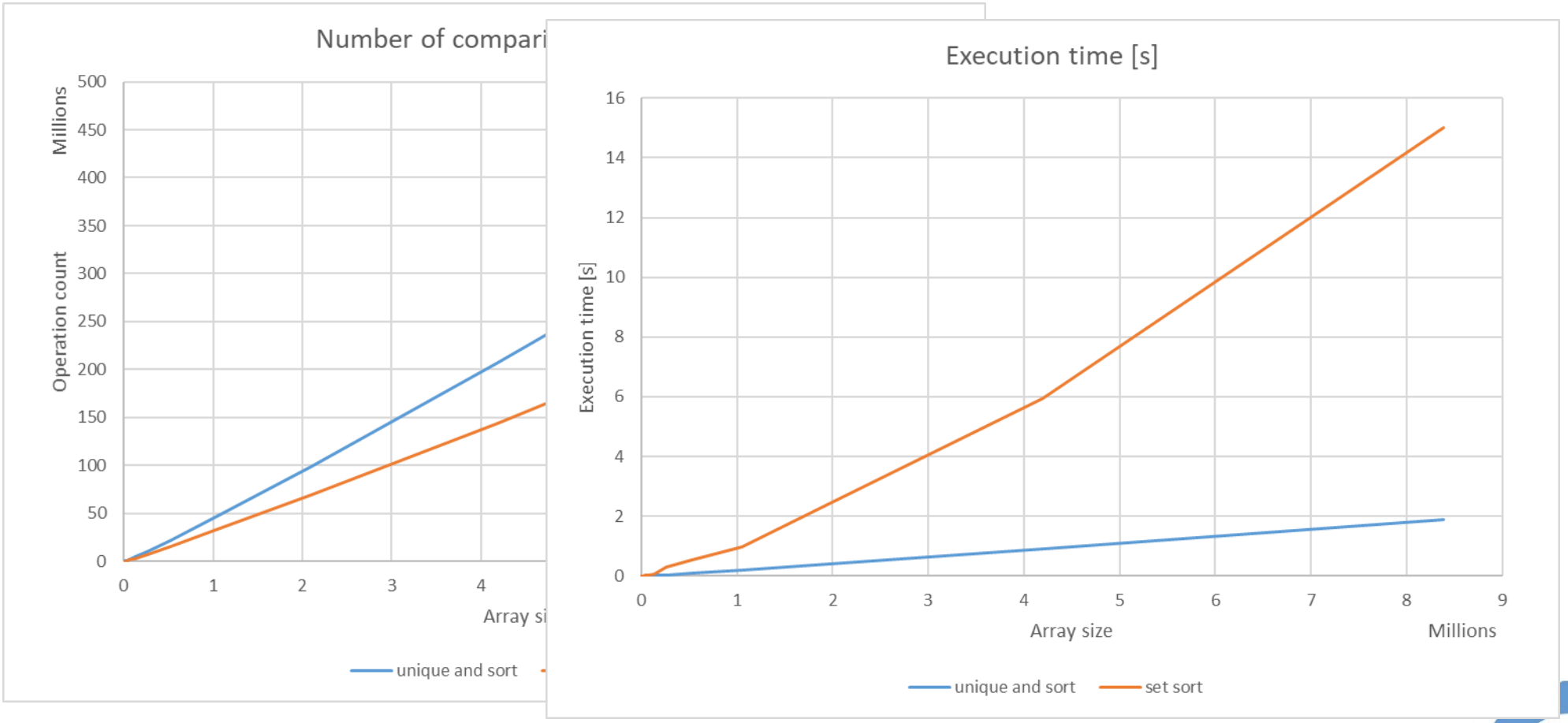


Using `std::sort` and `std::unique`

n	copy	assign	destruct	default	equal	less	construct	time
16	29	125	61					
32	61	421	125					
64	157	651	285					
128	404	1614	660					
256	856	3190	1368					
512	2200	7000	3224					
1024	4895	14949	6943					
2048	10202	31452	14298					
4096	23809	69595	32001					
8192	54365	151993	70749					
16384	104148	294590	136916					
32768	227532	630928	293068					
65536	512780	1374424	643852					
131072	1051039	2805207	1313183					
262144	2329354	6063902	2853642					
524288	4619934	12041526	5668510					
1048576	10067973	25735953	12165125					
2097152	21256236	53714098	25450540					
4194304	44364666	111139688	52753274					
8388608	93613867	232055273	110391083					



Number of unique elements



Conclusions

- Even if the number of operations is larger, the code may run faster
- Textbook solutions are often outdated
  - They are based on the understanding of how computers worked 15 years ago
- Understanding computer architecture is critically important in order to write efficient software
- Understanding Big-O complexity characteristics of algorithms (and data structure functionalities) is equally important
- All depends on the used data structures and how well those are aligned with how computers work
  - Always use `std::vector<T>`
  - If you think you can't use it, try again and find a way so you can

Exercise

- Measure and compare the amount of operations and the overall execution time for
  - `std::sort`
  - `std::stable_sort`
- Explain what you're seeing

Summary

- We know that `singleton<T>` and `instrumented<T>` conform to the type requirements (concepts) that all standard algorithms and containers expect
  - They can be used anywhere it would be valid to use `T`
- This guarantees that these types can be used with all algorithms and containers
  - This will not change the semantics of the algorithms
- The understanding of what concepts are assumed to apply for a given function or data structure is important
  - Allows to formalize in what contexts a function or data structure is guaranteed to produce correct results
- If a function or data structure works with a type that conforms to a set of concepts
  - We know that it will work with any other type that conforms to those concepts as well

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