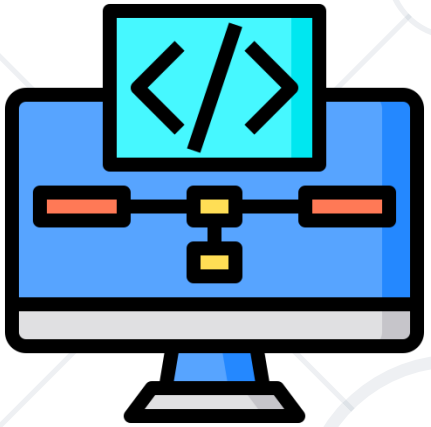
Rule of Three / Five / Zero



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Technical Trainers

Software University

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#cpp-oop

Resource Acquisition is Initialization

Associating Resources with Object Lifetime

Resource Acquisition is Initialization

- RAII – resource usage is tied to object lifetime
  - Objects acquire their resources on initialization
  - Objects release their resources on destruction
  - Effect: no resource leaks if no object leaks
- "Resources" – dynamic memory, streams, files, etc.
- Allocate in a constructor, deallocate in a destructor
  - Some cases might require allocation in methods
  - C++ guarantees destructor execution, even on error

RAII in the STL (1)

- C++ Streams are RAII
  - *E.g. file streams open file on construction & close on destruction*

```
void writeDataToFile(const std::string& data) {
  std::ifstream fileStream("log.txt", std::ios::in);
  //acquire resources

  istream << data << std::endl;

  istream.close(); //manually close the stream
} //destroy stream object. Even if the stream was not closed
  //the stream dtor would have closed it
```

RAII in the STL (2)

- All STL container classes are RAII
  - `vector<T>`, `list<T>`, `map<K, V>`, …
- `shared_ptr<T>` extends RAII to "multiple ownership"
  - Multiple objects own a resource
  - Release when a lifetime of last remaining owner ends

RAII

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Practice

Live Exercise in Class

Problem 1: SmartArray

- Implement a **SmartArray<T>** class that uses dynamic memory
  - Must be RAII, but STL containers/smart pointers are NOT allowed
  - Has size, has index access (with **operator[]**)
  - Can be resized
  - No support for copying/moving or assignment/move assignment
- *Bonus*: even more RAII
  - Don't use (directly) **new** methods
- *Bonus*: enable iteration (e.g. with range-based **for** loop)

Rule of Three / The Big Three

Destructors and Copies

- Constructor increases a static value, destructor decreases

```
void example() {
  Lecturer a("Dandelion", 1),
  b("Geralt", 1.3),
  c("Yen", 4.2);

  vector<Lecturer> lecturers;
  lecturers.push_back(a);
  lecturers.push_back(b);
  lecturers.push_back(c);
}
```

```
class Lecturer {
  static int Total;
...
public:
  Lecturer(...) ... { Total++; }
  ~Lecturer() { Total--; }
  ...
};

int Lecturer::Total= 0;
```

```
example(); cout << Lecturer::getTotal();
```

Copies Available -> Destructor Insufficient

- The example prints **-3** instead of **0** after all objects out of scope
- The problem is copy-construction/assignment
  - Counter not increased on copy
  - **3** locals -> **+3**
  - **3** copies into list -> **0** increments
  - Locals "destructed" -> **3-3=0**
  - List copies "destructed" -> **0-3=-3**

```
void example() {
  Lecturer a("Dandelion", 1)
  ...
  list<Lecturer> lecturers;
  all.push_back(a);
  ...
}
```

Copy that doesn't increment

Copies Available -> Destructor NOT Sufficient

LIVE DEMO

Destructor & Copies – Example (RAII issue)

- Let's use our **Array** from previous examples
  - Add destructor, auto-generated copy constructor/assignment
- Default copy constructor/assignment copies just the pointer
  - i.e. copy objects access and modify the same **data**
  - i.e. multiple **delete[]** at lifetime end on same data

```
void example() {
  Array arr(10);
  Array copyArr = arr;
  copyArr[3] = 42;
  cout << arr[3] // prints 42
}
```

arr does delete[] on data, then copyArr does delete[] on the same data

The Rule of Three

- If a class needs ONE of the following:
  - **Copy Constructor**
  - **Copy Assignment operator=**
  - **Destructor**
- Then it probably needs ALL of them:

```
IntArray(const IntArray& other) { ... }

IntArray& operator=(const IntArray& other) { ... }

~IntArray() { ... }
```

Rule of Three – Copy Construct/Assign

- General guidelines:
  - `new` can cause errors – make sure object state valid in that case
  - Free any current object resources
- Patterns:
  - Copy other object data into local variable, then set `this` fields
  - Extract a function to reuse code for copy construct & assign
  - ... or use the copy-and-swap idiom

Rule of Three

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Copy-and-Swap Idiom

Copy-and-Swap Idiom (1)

- Copy and swap idiom is used for simpler handling of dynamic resource (preventing **new** / **delete** / **delete[]** errors)
- Image a simple SmartArray implementation:

```
template <typename T>
class SmartArray {
// …
private:
  size_t _size;
  T *_data;
} ;
```

Copy-and-Swap Idiom (2)

- The constructor / destructor are trivial:

```
SmartArray(size_t size)
  : _size(size), _data(_size ? new T[_size] { } : nullptr) {
}
```

```
~SmartArray() {
  if (_data) {
    delete[] _data;
  }
}
```

Copy-and-Swap Idiom (3)

- The copy constructor is also trivial:

```
SmartArray(const SmartArray &other)
  : _size(other._size), _data(_size ? new T[_size] { } : nullptr) {
    std::copy(other._data, other._data + _size, _data);
}
```

Copy-and-Swap Idiom (4)

- Here comes the interesting part:
  - We provide a friend public method swap that can efficiently swap 2 objects:

```
friend void swap(SmartArray &first, SmartArray &second) {
  std::swap(first._size, second._size);
  std::swap(first._data, second._data);
}
```

  - Then the copy assignment operator is actually making a copy of the object:

```
SmartArray& operator=(SmartArray other) {
  swap(*this, other);
  return *this;
}
```

Copy-and-Swap Idiom (5)

- This way a new object is created, it is being populated by the copy constructor
- Then swapped with the real object
- The destructor of the previous object (previous this) takes care of deleting dynamic allocated resources (if any)

Practice

Live Exercise in Class

Problem 2: Rule of Three for `SmartArray`

- Implement the Rule of Three for the **`SmartArray<T>`** class
- Bonus: implement it using the copy-and-swap idiom

Quick Quiz TIME:

What the following program do?

a) print 42 and exit successfully

b) produce compilation error

c) print 42 and give a runtime error

d) undefined behaviour

```
int main() {
  SmartArray<int> arr(5);
  arr[2] = 42;

  SmartArray<int> arr2 = std::move(arr);
  std::cout << arr2[2] << std::endl;
  return 0;
}
```

```
template <typename T>
class SmartArray {
public:
  SmartArray(size_t size)
      : _size(size), _data(_size ? new
T[_size] { } : nullptr) {
  }

  SmartArray(SmartArray &&other)
      : _size(other._size),
_data(other._data) {
  }

  ~SmartArray() {
    if (_data) {
      delete[] _data;
    }
  }
//...
};
```

C++ MOVE CONSTRUCTOR PITFALLS

When a custom implementation of move constructor is provided - the owned resources have to be actually **stolen**.
When the pointer is moved to the new objects - they have to be reset from the previous object.

Effectively assigning them a nullptr (or empty value).

The Rule of Five

The Rule of Five

- If a class needs ONE of the following:
  - **Copy Constructor**
  - **Copy Assignment operator=**
  - **Destructor**
  - **Move Constructor**
  - **Move Assignment operator=**

Then it probably needs ALL of them:

```
IntArray(const IntArray& other) { ... }
IntArray& operator=(const IntArray& other) { ... }
IntArray(IntArray&& other) { ... }
IntArray& operator=(IntArray&& other) { ... }
~IntArray() { ... }
```

Rule of Five = Rule of Three

- Rule of Five = Rule of Three
- Move construct/assign
  - Custom implementation could also be provided for Move Constructor and Move Assignment Operator

```
SmartArray(SmartArray &&other) : _data(other._data), _size(other._size) {
  other._size = 0;
  other._data = nullptr;
}
```

Rule of Five = Rule of Three

```
SmartArray& operator=(SmartArray &&other) {
  if (this != &other) {
    _data = other._data;
    _size = other._size;

    other._size = 0;
    other._data = nullptr;
  }
  return *this;
}
```

Copy and swap Idiom for the Rule of Five (1)

- In the implementation of copy and swap for the Rule of Three the copy assignment operator was implemented as such:

```
SmartArray& operator=(SmartArray other) {
  swap(*this, other);
  return *this;
}
```

Copy and swap Idiom for the Rule of Five (2)

- If move assignment operator is added

```
SmartArray& operator=(SmartArray &&other) {
  //...
}
```

- The compiler will be ambiguous, which assignment operator you want to call -> get a compilation error
- This would mean that we have to keep the current implementation of the copy assignment operator, which now calls only … assignment operator

The Rule of Four … and a half

The Rule of Four … and a half

- In order to enable the **Copy and Swap Idiom** for the **move** methods as well
- Only providing the **move constructor** should be implemented

```
// initialize using the default constructor first
SmartArray(SmartArray &&other) : SmartArray(0) {
  swap(*this, other);
}
```

The Rule of Four … and a half

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Single Responsibility

- If a class has one of **The Three / Five**, then:
  - It manages a resource (memory or something else)
  - It should manage a **single** resource
  - It should not do anything other than manage the resource
- So, need a resource? Wrap it in a class
  - Internal code deals with constructors / destructors / etc.
- Having such classes avoids the Rule of Three / Five

Rule of Zero

Delegating Resource Management

Rule of Zero

- STL has containers, smart pointers, etc.
  - Wrap other resources with classes implementing Rule of 3 (or 5)
- All remaining classes use the above, so:
  - No need for explicit destructor
  - No need for explicit copy-constructor
  - No need for explicit copy-assignment operator
- *If you can – avoid resource management*

Rule of Zero for Array Class

- Avoid memory management – `shared_ptr<int> data;`
- Tell `shared_ptr<T>` to release using array `delete[]`:
  - Second parameter accepts code to execute for deletion
  - `data(..., default_delete<int[]>)`
  - or `data(..., [](int* p) { delete[] p; })`
- No destructors, No copy construction, No copy assignment
- Or just use a `vector<T>`

Rule of Zero

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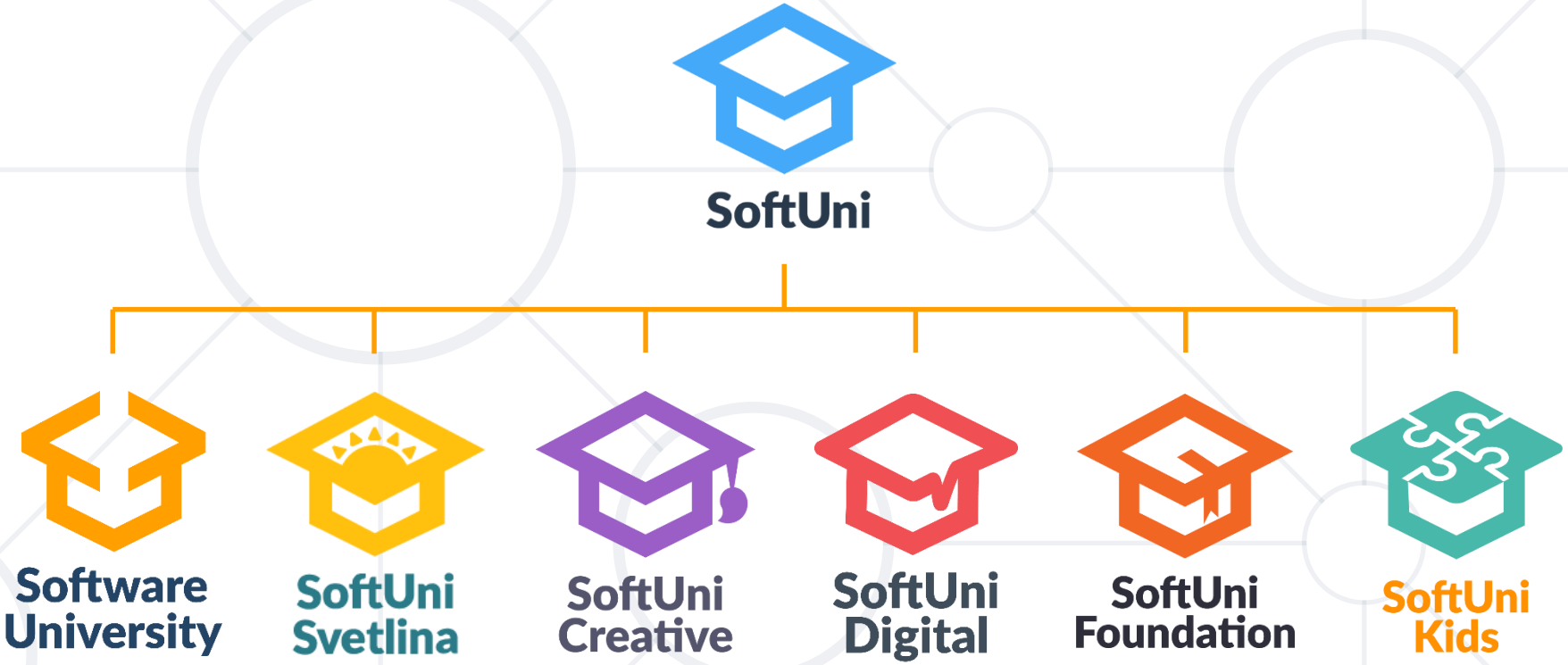
Summary

- RAII – C++ pattern of initializing memory in the constructor
  - **Rule of Three** – implement or disable copy members
- **Rule of Zero** – delegate resource management to other classes

Questions?



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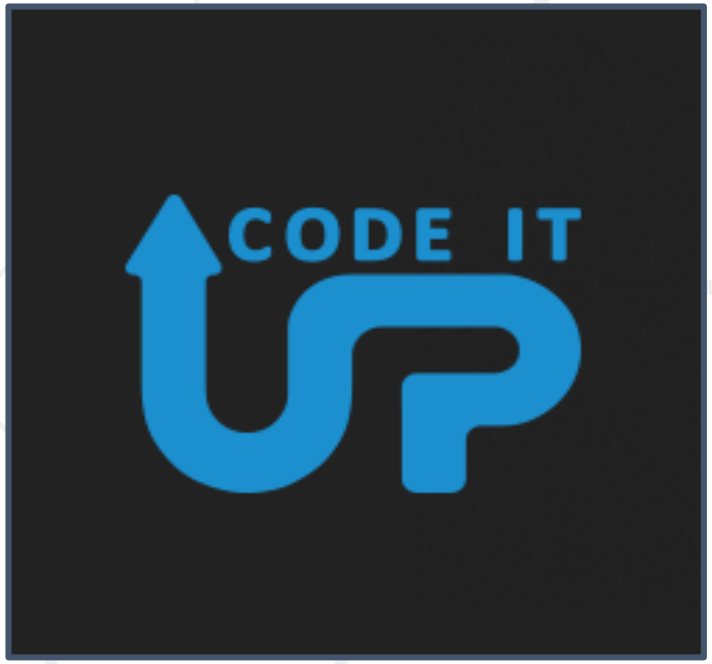

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