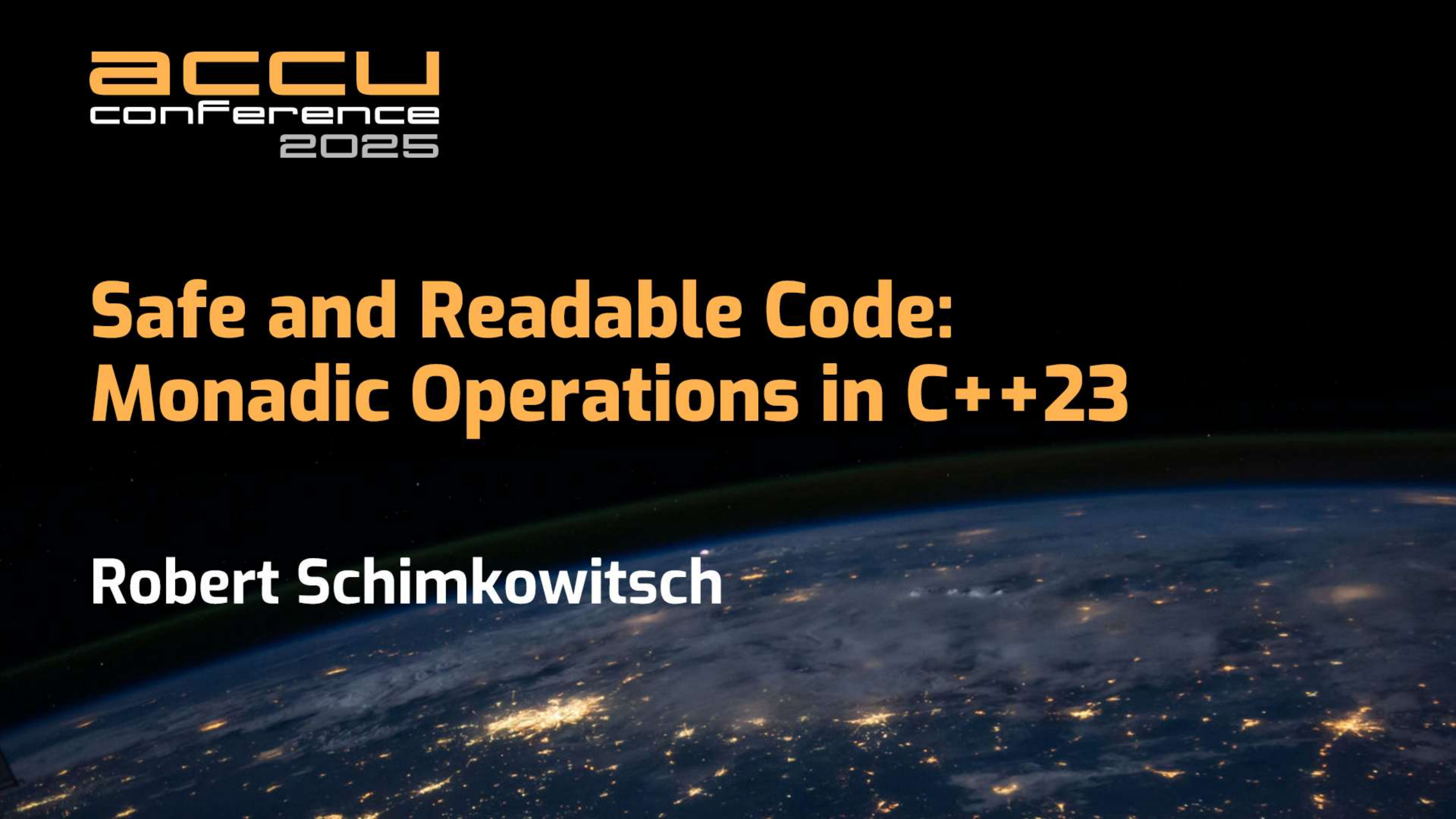
accu conference 2025

Safe and Readable Code: Monadic Operations in C++23

Robert Schimkowitsch



About Me

Senior Software Engineer @ Andritz Hydro

Multi-platform
desktop systems (Qt)

Client architecture

Requirement refinement

Mentoring junior colleagues

Robert Schimkowitsch

https://mastodon.social/@asperamanca
https://github.com/Asperamanca/
https://cppusergroupvienna.org/

Co-Funder of
C++ User Group Vienna

Handling Potential Failure

```
bool getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    CElement element;
    if ( ! getElement(db, key, element))          { return false; }

    CTable table;
    if ( ! getTable(element, table))              { return false; }

    CCell cell;
    if ( ! getCell(table, location, cell))        { return false; }

    int value;
    if ( ! getNumericCellValue(cell, value))      { return false; }

    result = (value < 0);
    return true;
}
```

Handling Potential Failure

```
bool getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    CElement element;
    if ( !getElement(db, key, element))          { return false; }

    CTable table;
    if ( !getTable(element, table))              { return false; }

    CCell cell;
    if ( !getCell(table, location, cell))        { return false; }

    int value;
    if ( !getNumericCellValue(cell, value))      { return false; }

    result = (value < 0);
    return true;
}
```

...With Exceptions

```
throw out_of_range("row out of bounds");
```

```
bool isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    auto table = getTable(getElement(db,key));
    auto cell = getCell(table, cellLocation);
    return (getNumericCellValue(cell) < 0);
}
```

```
Call stack
getCell                         test.cpp     25
isIntCellValueNegative          test.cpp     60
tryCall<int (__cdecl&...        test.cpp     38
testTable                       test.cpp     107
main                            test.cpp     9
...
```

```
catch (const invalid_argument& e)
{ //...
}
catch (const out_of_range& e)
{ //...
}
catch (...) //...
```

https://godbolt.org/z/EMPj9nYW5

But I Can't or Won't use Exceptions!

```
bool getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    CElement element;
    if ( ! getElement(db, key, element))          { return false; }

    CTable table;
    if ( ! getTable(element, table))              { return false; }

    CCell cell;
    if ( ! getCell(table, location, cell))        { return false; }

    int value;
    if ( ! getNumericCellValue(cell, value))      { return false; }

    result = (value < 0);
    return true;
}
```

Does an Error Flag Help?

```
class CMyClass
{
    //...
    bool m_bError{false};
};

bool CMyClass::getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    auto table = getTable(getElement(db,key))
    auto cell = getCell(table, location))
    auto value = getNumericCellValue(cell))
    if (m_bError)
    {
       return false;
    }
    result = (value < 0);
    return true;
}
```

Does an Error Flag Help?

```
class CMyClass
{
    //...
    bool m_bError{false};
};

bool CMyClass::getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    auto table = getTable(getElement(db,key))
    auto cell = getCell(table, location))
    auto value = getNumericCellValue(cell))
    if (m_bError)
    {
       return false;
    }
    result = (value < 0);
    return true;
}
```

```
CTable CMyClass::getTable
{
    if (m_bError)
    {
        return{};
    }
    //...
```

Does an Error Flag Help?

```
class CMyClass
{
    //...
    bool m_bError{false};
};

bool CMyClass::getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    auto table = getTable(getElement(db,key))
    auto cell = getCell(table, location))
    auto value = getNumericCellValue(cell))
    if (m_bError)
    {
       return false;
    }
    result = (value < 0);
    return true;
}
```

Fixing the Return Type with…

```
bool getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    CElement element;
    if ( ! getElement(db, key, element))          { return false; }

    CTable table;
    if ( ! getTable(element, table))              { return false; }

    CCell cell;
    if ( ! getCell(table, location, cell))        { return false; }

    int value;
    if ( ! getNumericCellValue(cell, value))      { return false; }

    result = (value < 0);
    return true;
}
```

Fixing the Return Type with std::optional

```
optional<bool> isIntCellValueNegative
    (CDb db, Key key, CLocation location)
{
    auto oElement = getElement(db,key);
    if ( ! oElement.has_value())        { return {}; }

    auto oTable = getTable(oElement.value());
    if ( ! oTable.has_value())          { return {}; }

    auto oCell = getCell(oTable.value(),location);
    if ( ! oCell.has_value())           { return {}; }

    auto oValue = getNumericCellValue(oCell.value());
    if ( ! oValue.has_value())          { return {}; }


    return (oValue.value() < 0);
}
```

C++23: Begone, Boilerplate!

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative);
}
```

Goals

1. Understand what functors and monads do
2. Use monadic operations from std without much trouble
3. Have leads & references for further exploration

Code on Slides

```
// Don't copy code from slides!
// Use GitHub or Compiler Explorer links
//  (see end of presentation)
```

```
string s;                 // Standard library symbols are lime
foo();                    // Callables are orange
template<class TValue>    // Template types are purple
class CUser;              // User-defined types are blue
```

```
// Slides have been cleaned of dinosaurs
// but may contain traces of unicorn
```

Functors

MAP, WRAP, TRANSFORM

Is this a Functor?

```
class CNegator
{
public:
    int operator()(const int value) const
    {
        return -value;
    }
};

// ...

CNegator negator;
auto x = negator(5); // -5
```

https://godbolt.org/z/9er1Yq9or

A Simple Sequence

```
double calcArea(double radius);
string formatArea(double area);

string foo1(double radius)
{
   return formatArea(calcArea(radius));
}
```

https://godbolt.org/z/9er1Yq9or

A Simple Sequence

```
double calcArea(double radius);
string formatArea(double area);

string foo1(double radius)
{
   return formatArea(calcArea(radius));
}
```

https://godbolt.org/z/9er1Yq9or

Adding a Version with a std::vector of Input Values

```
double calcArea(double radius);
string formatArea(double area);

string foo1(double radius)
{
   return formatArea(calcArea(radius));
}

vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}
```

https://godbolt.org/z/9er1Yq9or

Adding a Version with a std::vector of Input Values

```
double calcArea(double radius);
string formatArea(double area);

string foo1(double radius)
{
   return formatArea(calcArea(radius));
}

vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}
```

https://godbolt.org/z/9er1Yq9or

Adding a Version with a std::vector of Input Values

```
double calcArea(double radius);
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{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}
```

https://godbolt.org/z/9er1Yq9or

Adding a Version with a std::vector of Input Values

```
string foo1(double radius)
{
   return formatArea(calcArea(radius));
}

vector<string> fooVec(vector<double
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}
```

Handles vector part

Handles element part

Violation of Single Responsibility!
Vector-related code will be duplicated

https://godbolt.org/z/9er1Yq9or

A Minimal Functor

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   auto calcVecArea = liftVec<double>(calcArea);
   auto formatVecOutput = liftVec<double>(formatArea);
   return formatVecOutput(calcVecArea(vecRadius));
}
```

https://godbolt.org/z/9er1Yq9or

A Minimal Functor

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   auto calcVecArea = liftVec<double>(calcArea);
   auto formatVecOutput = liftVec<double>(formatArea);
   return formatVecOutput(calcVecArea(vecRadius));
}
```

New function
created by lifting
our old one

https://godbolt.org/z/9er1Yq9or

A Minimal Functor

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   auto calcVecArea = liftVec<double>(calcArea);
   auto formatVecOutput = liftVec<double>(formatArea);
   return formatVecOutput(calcVecArea(vecRadius));
}
```

We pass a callable here

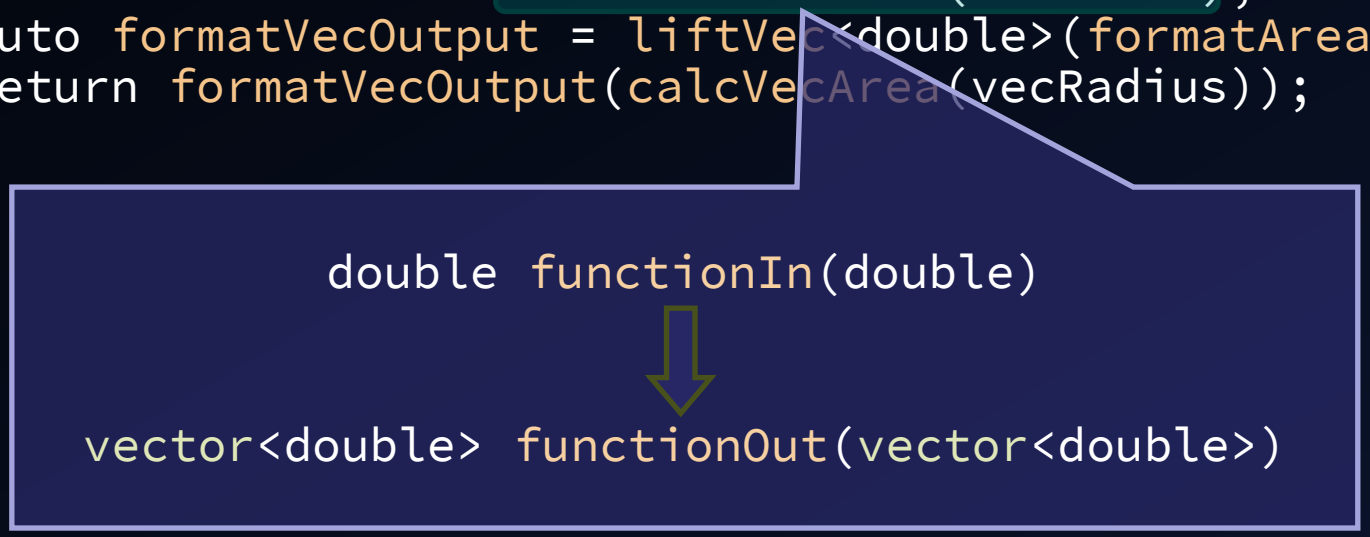
New function
created by lifting
our old one

https://godbolt.org/z/9er1Yq9or

A Minimal Functor

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   auto calcVecArea = liftVec<double>(calcArea);
   auto formatVecOutput = liftVec<double>(formatArea);
   return formatVecOutput(calcVecArea(vecRadius));
}
```

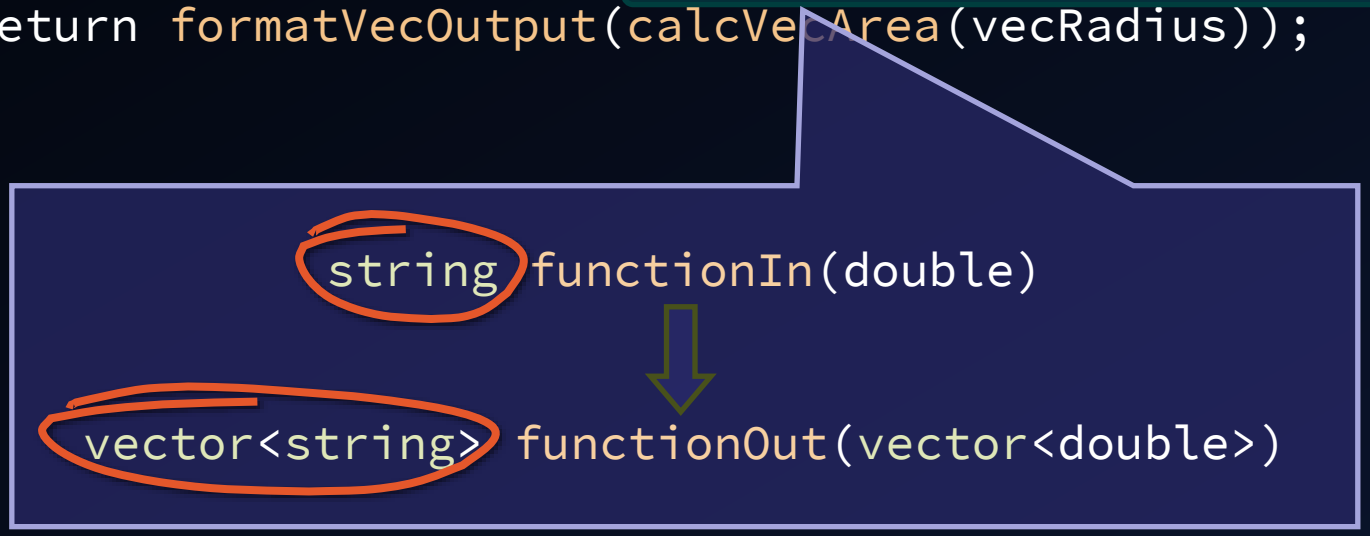


https://godbolt.org/z/9er1Yq9or

A Minimal Functor

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   auto calcVecArea = liftVec<double>(calcArea);
   auto formatVecOutput = liftVec<double>(formatArea);
   return formatVecOutput(calcVecArea(vecRadius));
}
```



https://godbolt.org/z/9er1Yq9or

A Minimal Functor

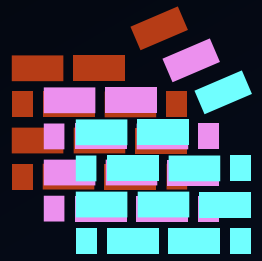
```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   auto calcVecArea = liftVec<double>(calcArea);
   auto formatVecOutput = liftVec<double>(formatArea);
   return formatVecOutput(calcVecArea(vecRadius));
}
```

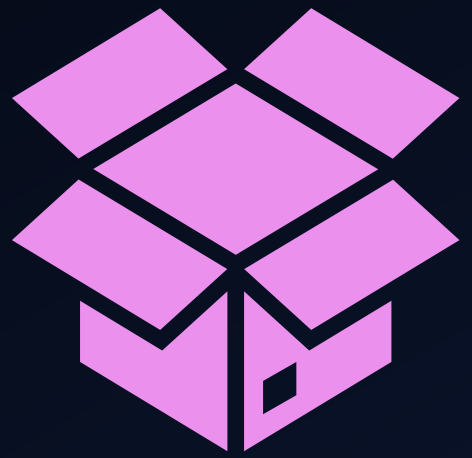
'Vector' part is added by liftVec
and implemented once
We only define the sequence of calls

https://godbolt.org/z/9er1Yq9or

A Functor Wrapper as a Magic Box...

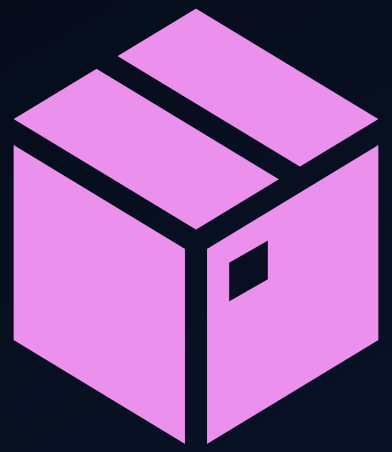


Put in a vector of bricks...



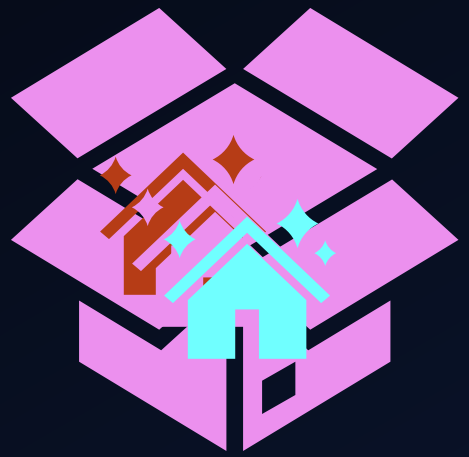
A Functor Wrapper as a Magic Box...

...send in a worker with a plan...
(still only one!)



A Functor Wrapper as a Magic Box...

...get a vector of houses



Using the Magic Box

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   return CFunctorVec{vecRadii}.transform(calcArea)
                               .transform(formatArea)
                               .result();
}
```

https://godbolt.org/z/9er1Yq9or

Using the Magic Box

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   return CFunctorVec{vecRadii}.transform(calcArea)
                               .transform(formatArea)
                               .result();
}
```

We pass a callable here

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Using the Magic Box

```
double calcArea(double radius);
string formatArea(double area);


vector<string> fooVec(vector<double> vecRadii)
{
   return CFunctorVec{vecRadii}.transform(calcArea)
                               .transform(formatArea)
                               .result();
}
```

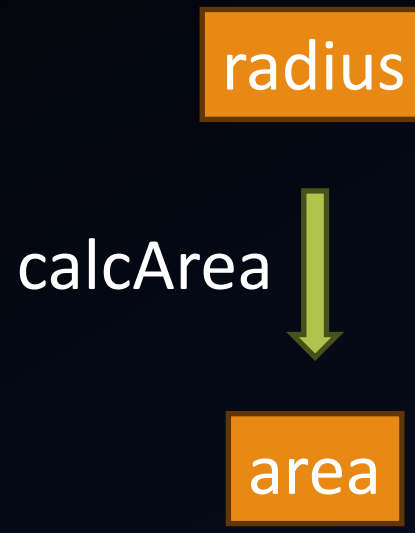
The 'Vector' part happens in CFunctorVec
and is implemented once
I only define the sequence of calls

https://godbolt.org/z/9er1Yq9or

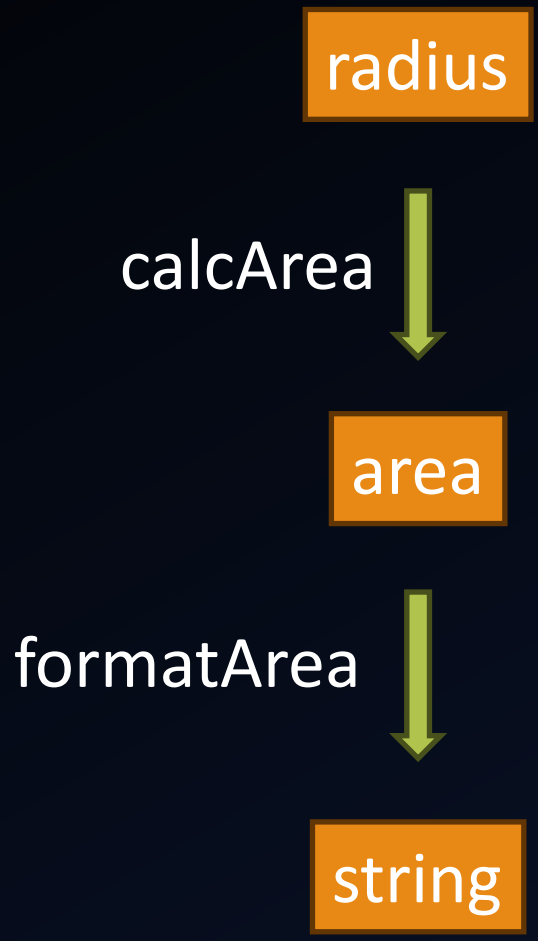
Functor, Step by Step

radius

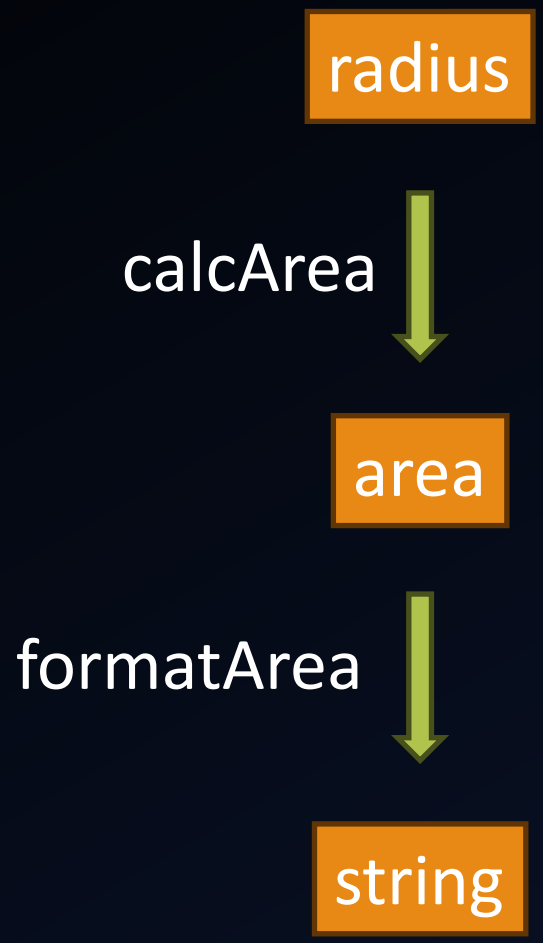
Functor, Step by Step



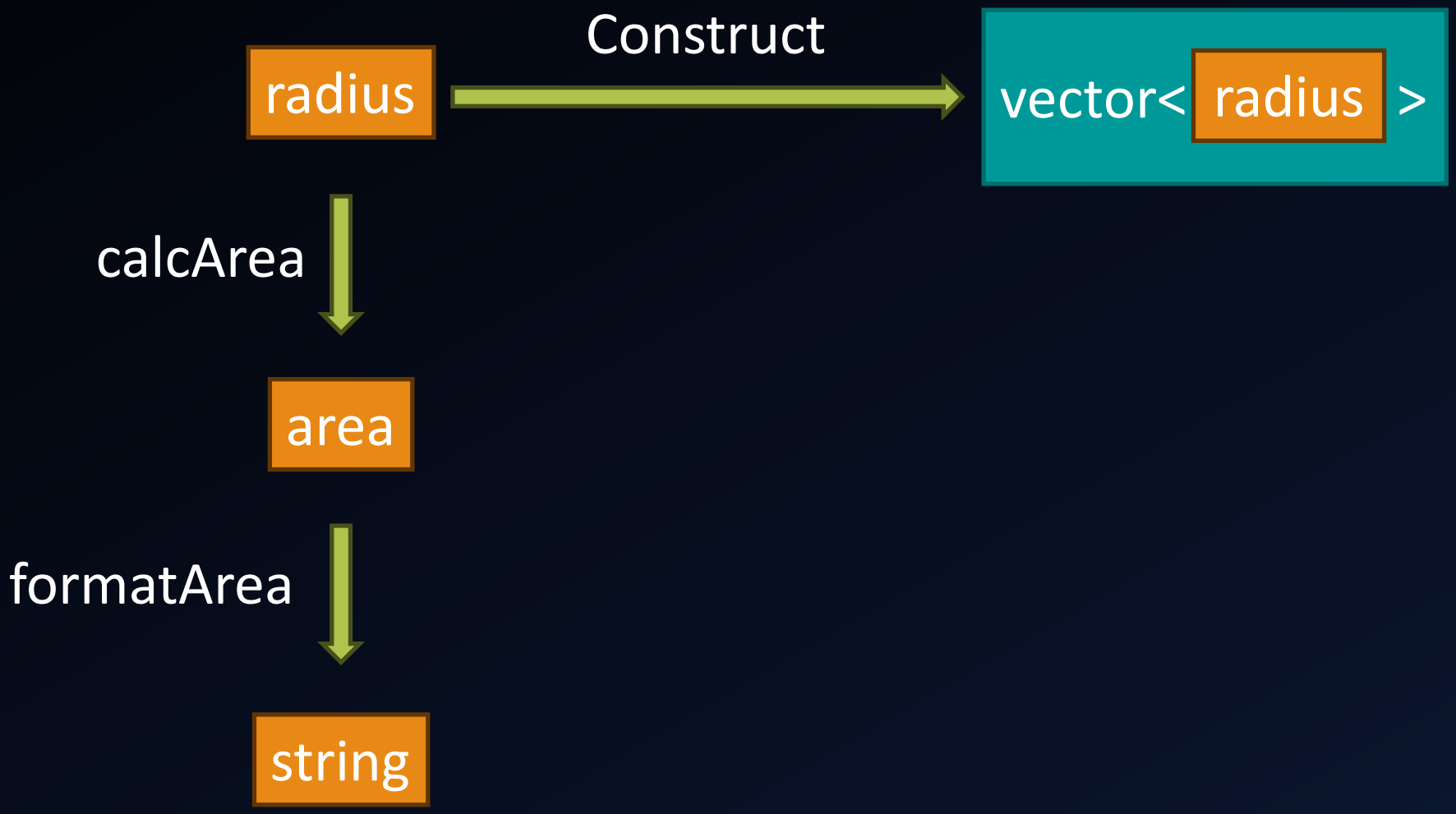
Functor, Step by Step



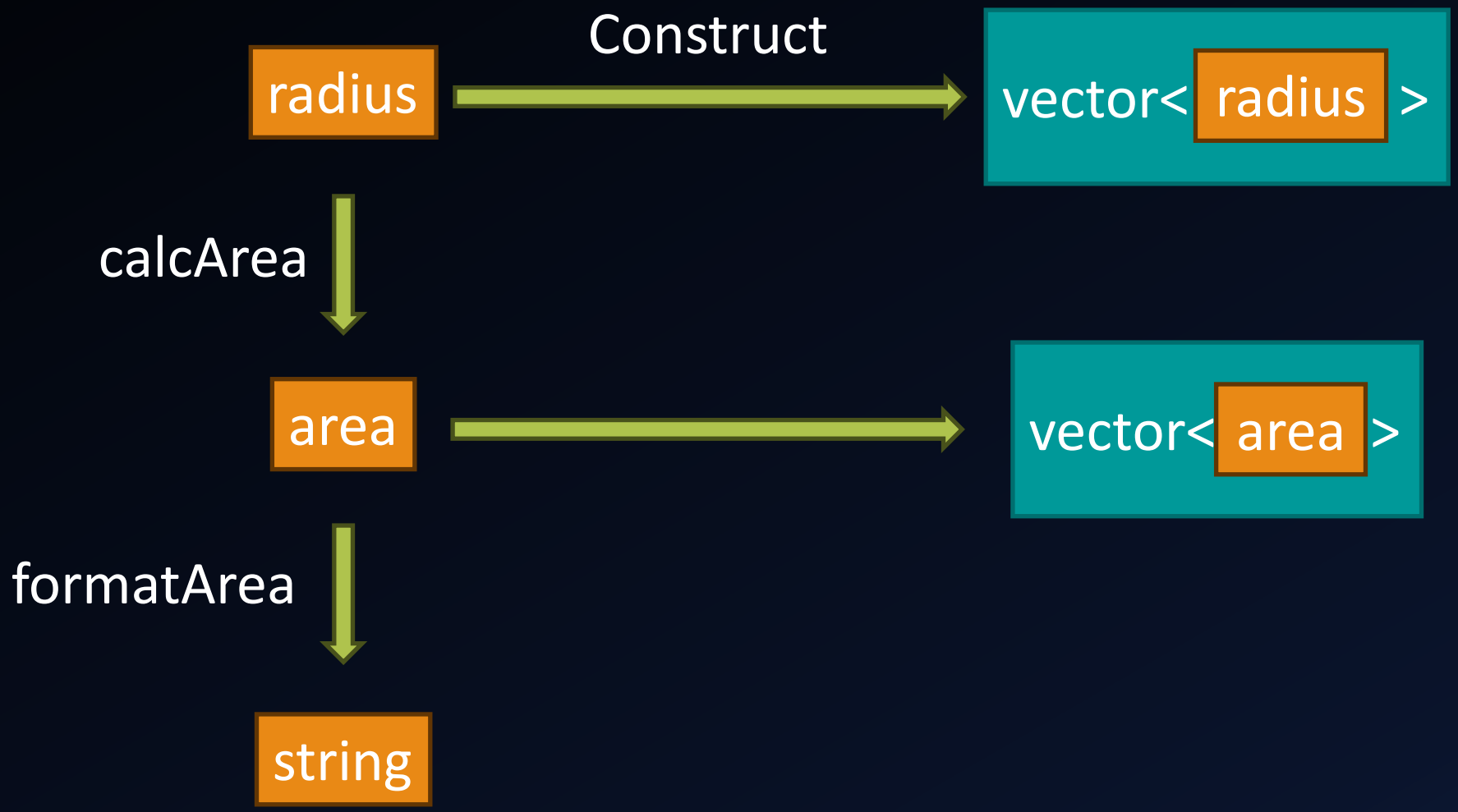
Functor, Step by Step



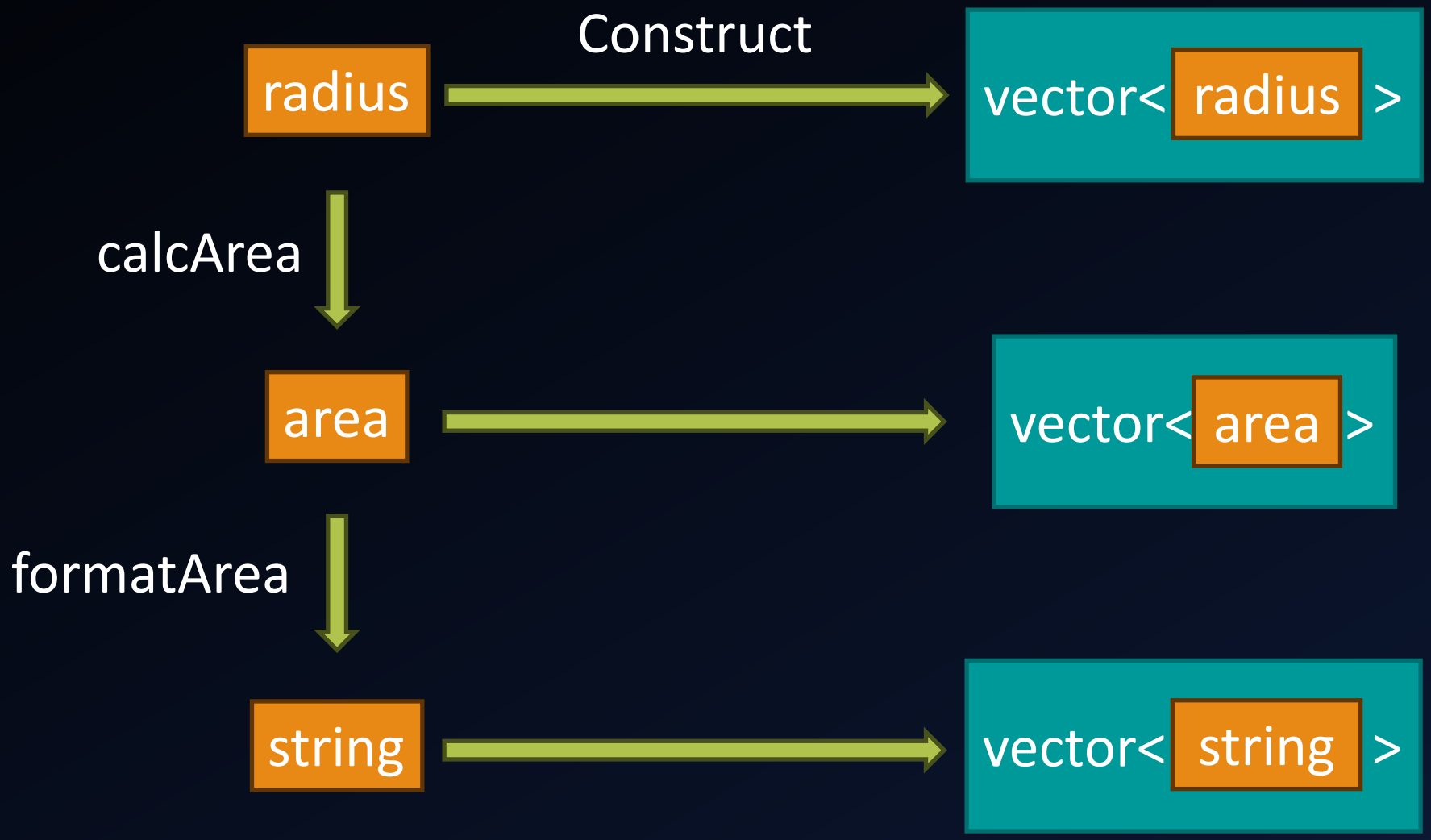
Functor, Step by Step



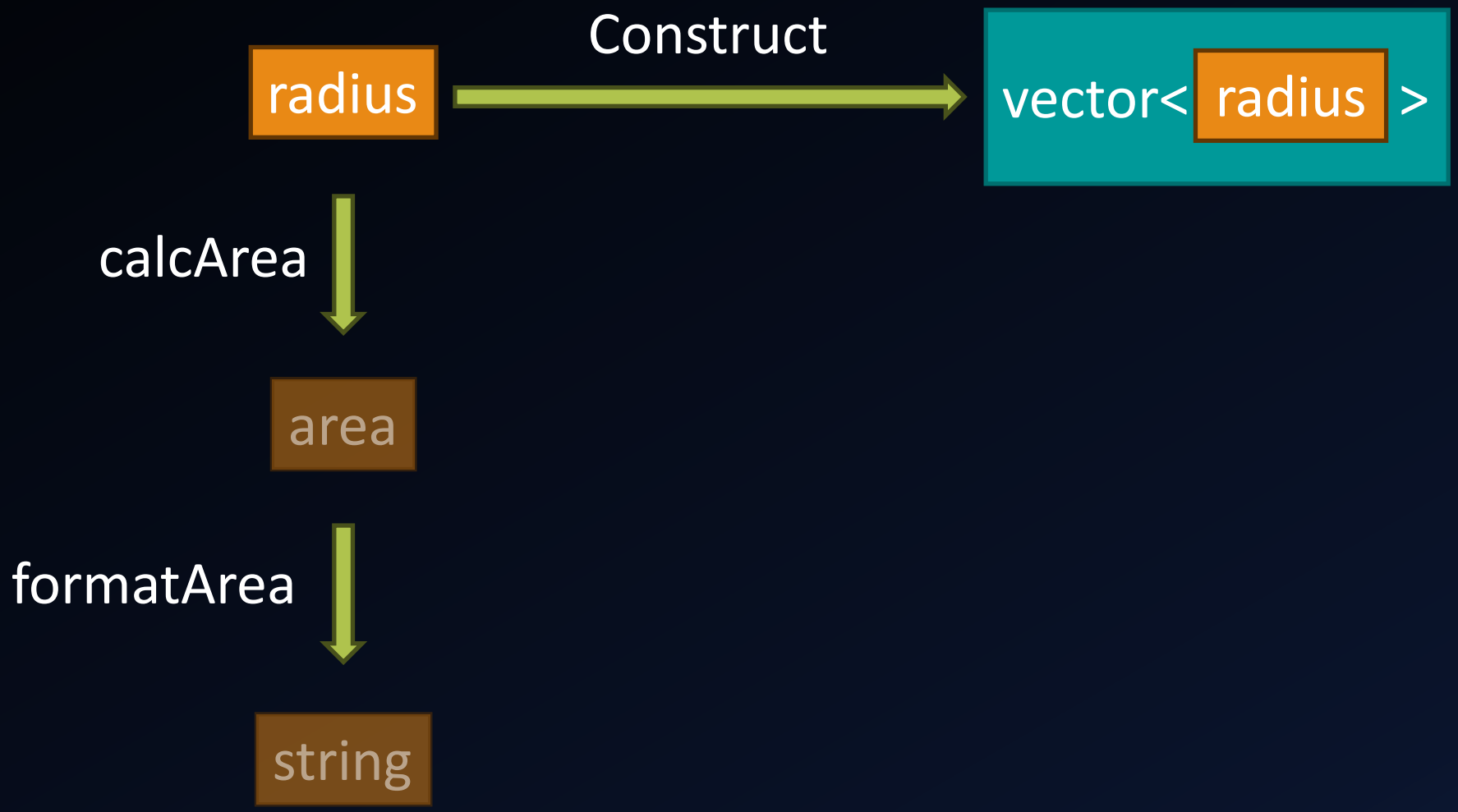
Functor, Step by Step



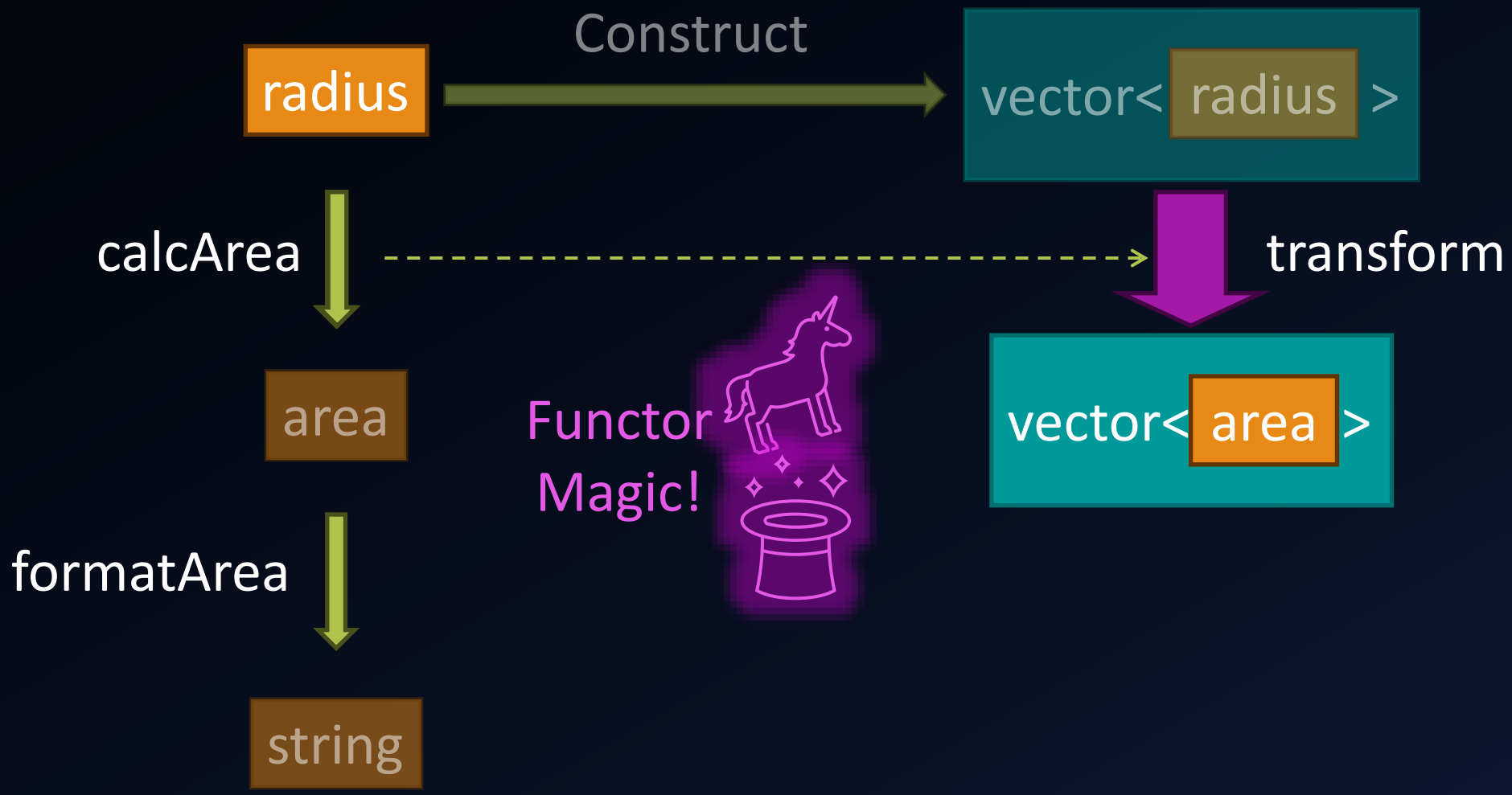
Functor, Step by Step



Functor, Step by Step



Now it's a Functor!



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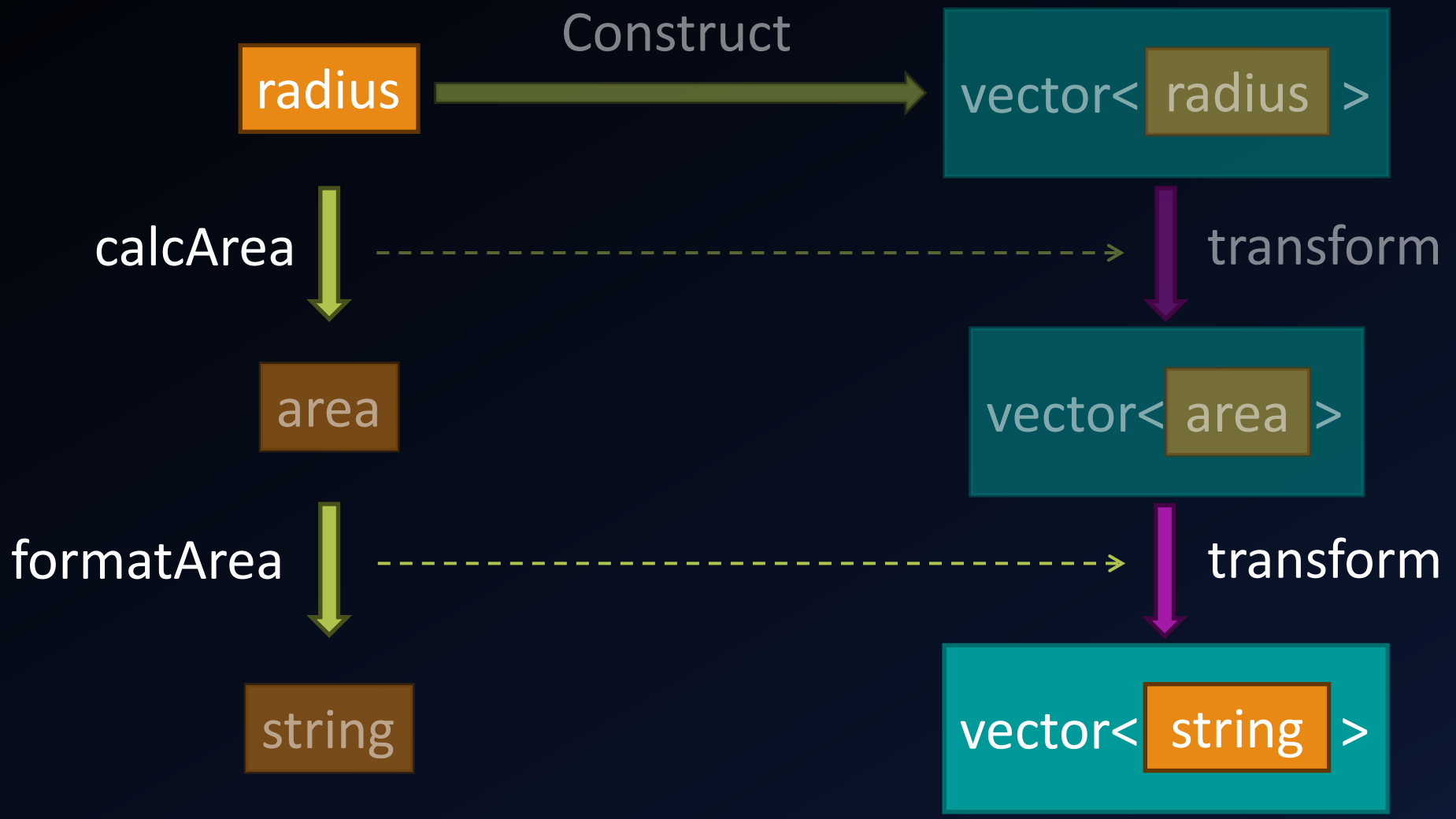
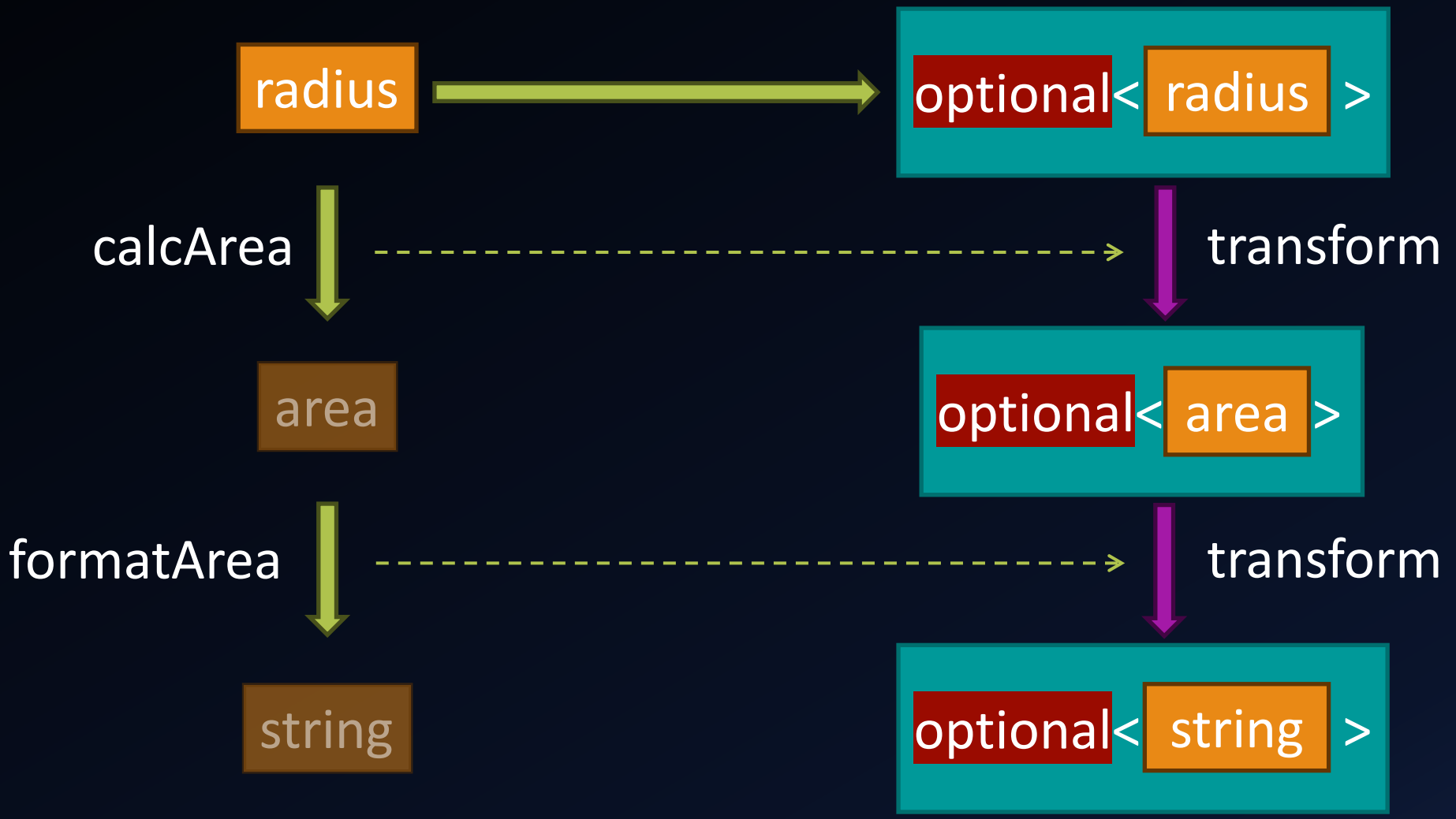
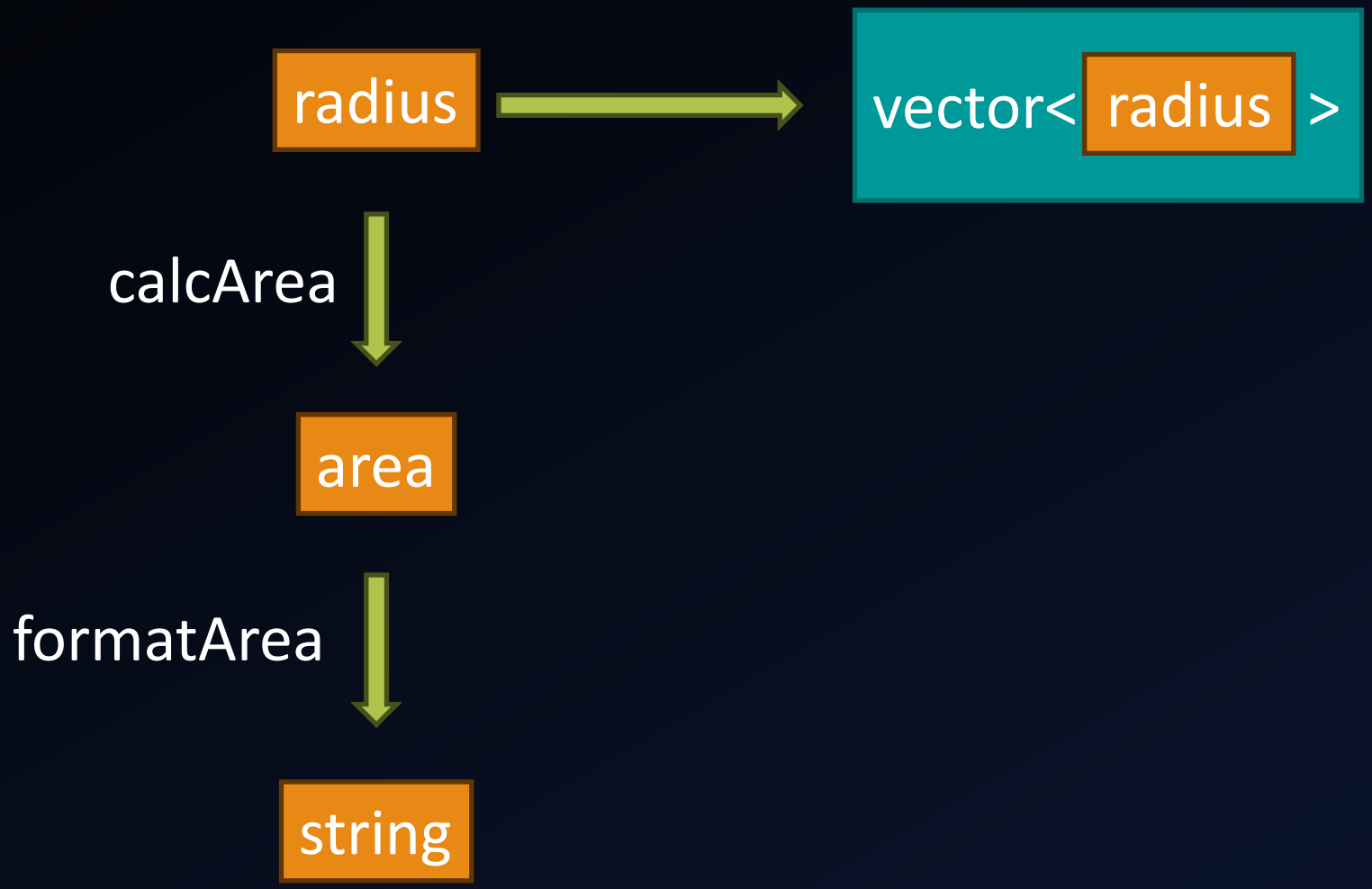


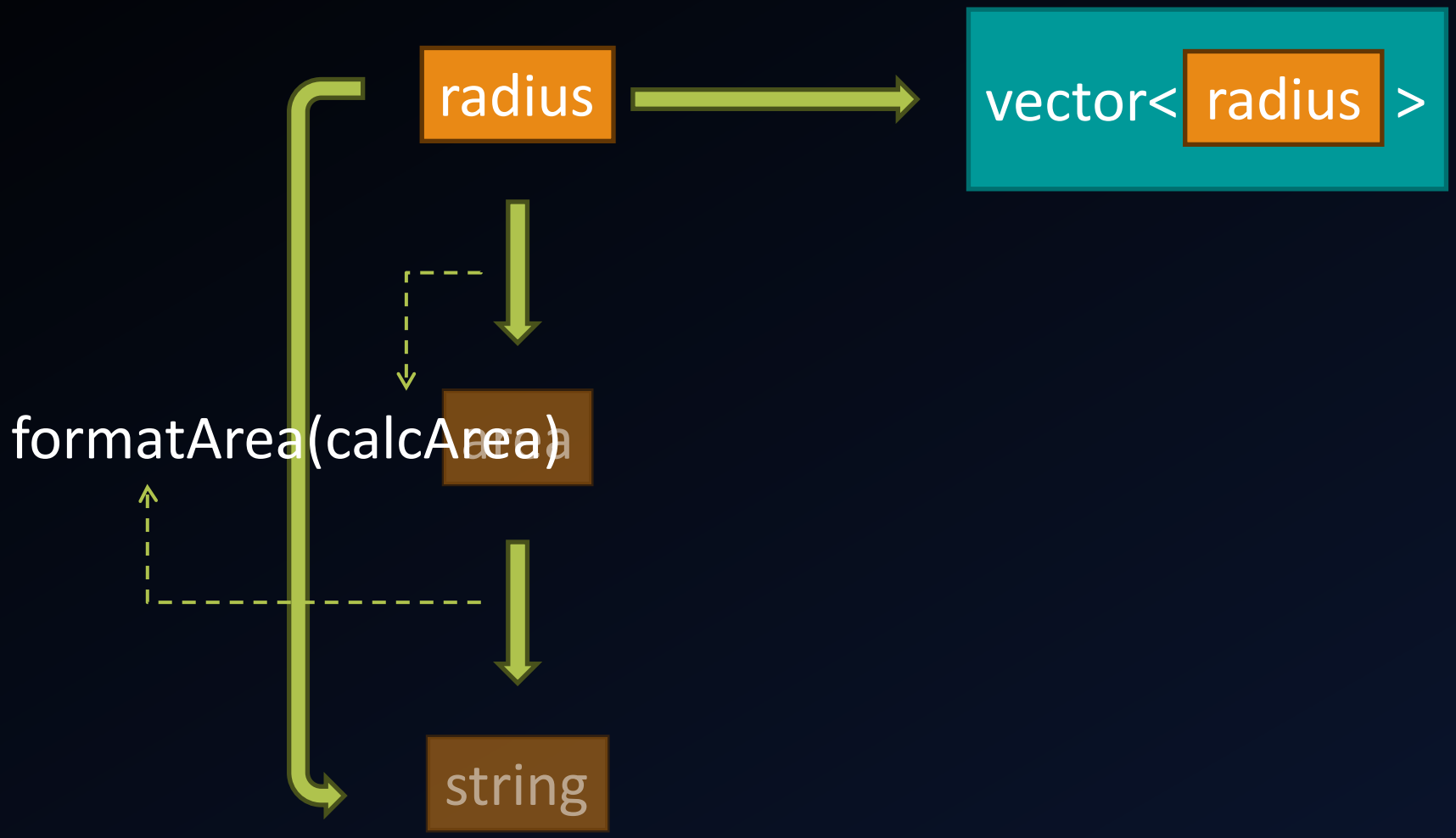
Replace the Functor Using the same Functions



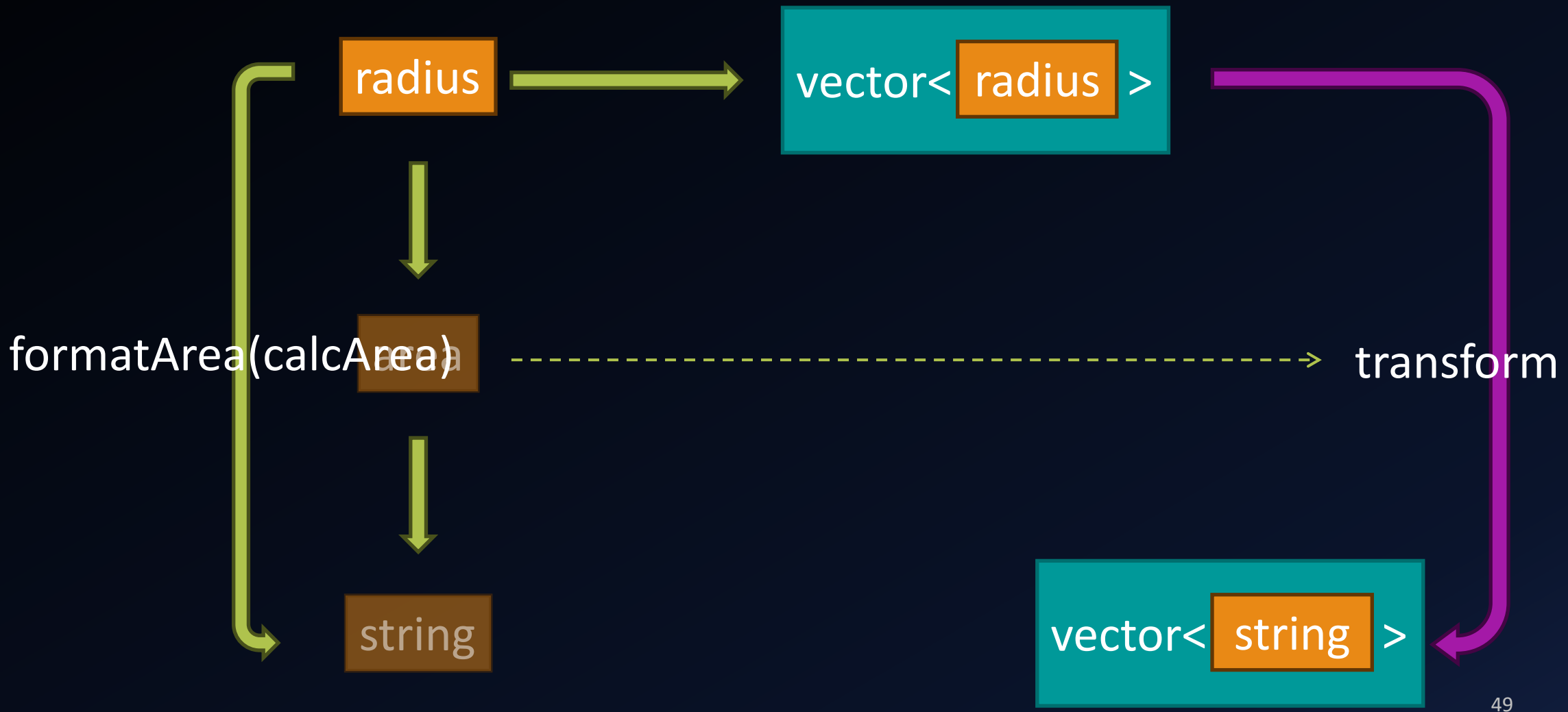
Two Rules for Functors



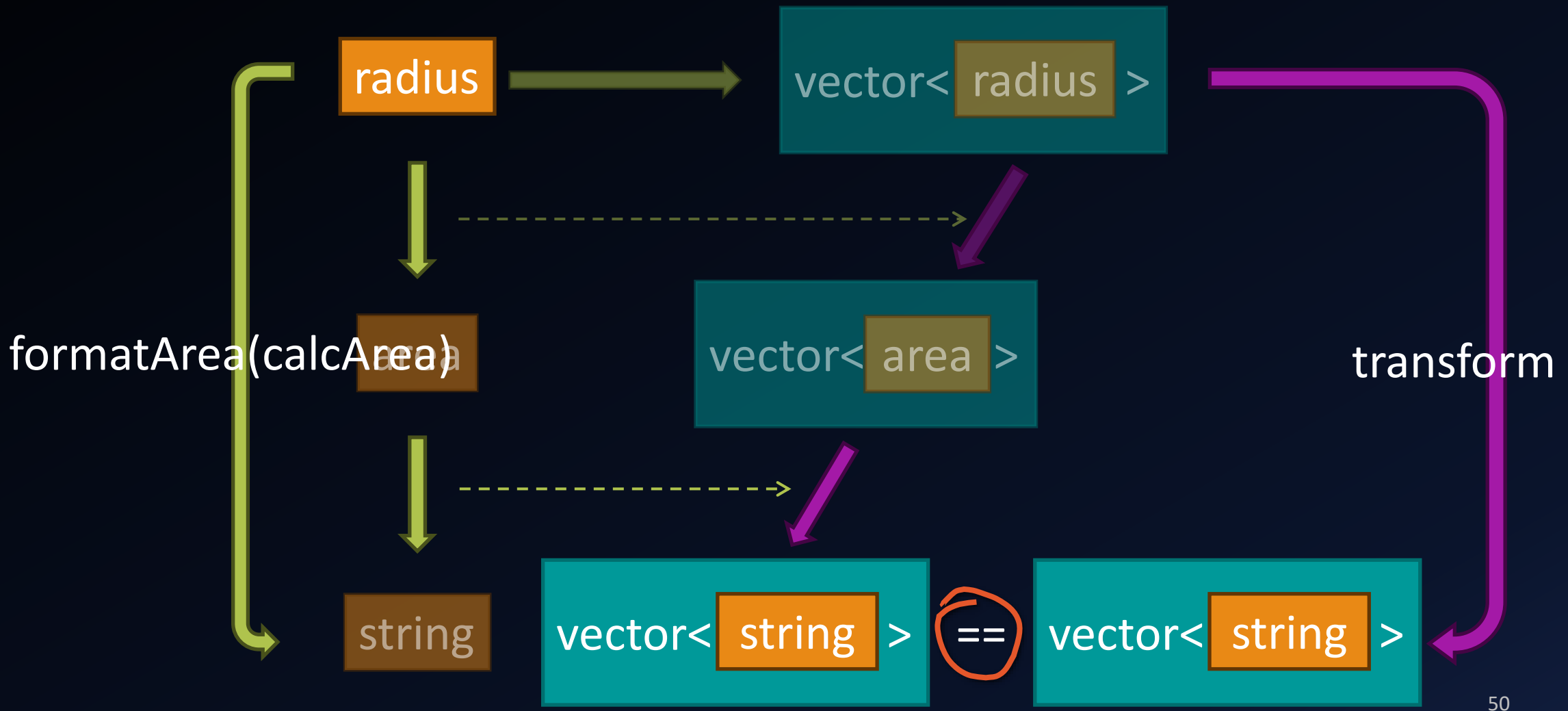
Rule #1: Composition Reflects in the Functor



Rule #1: Composition Reflects in the Functor



Rule #1: Composition Reflects in the Functor



Rule #2: Identity is Preserved

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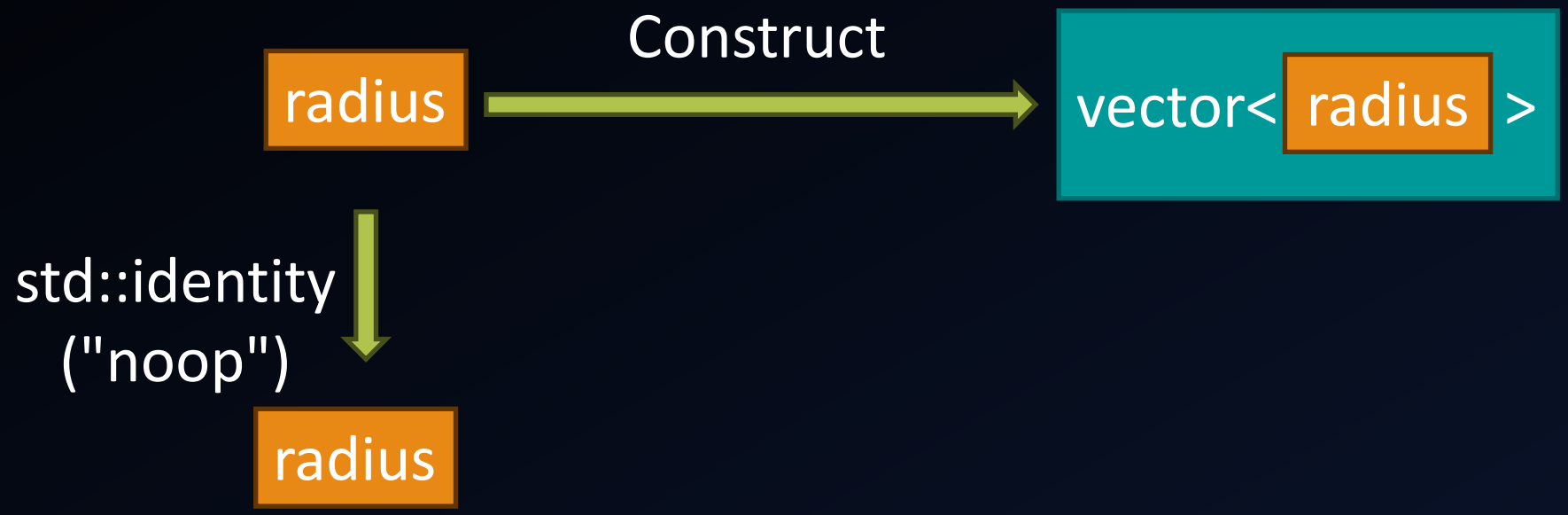
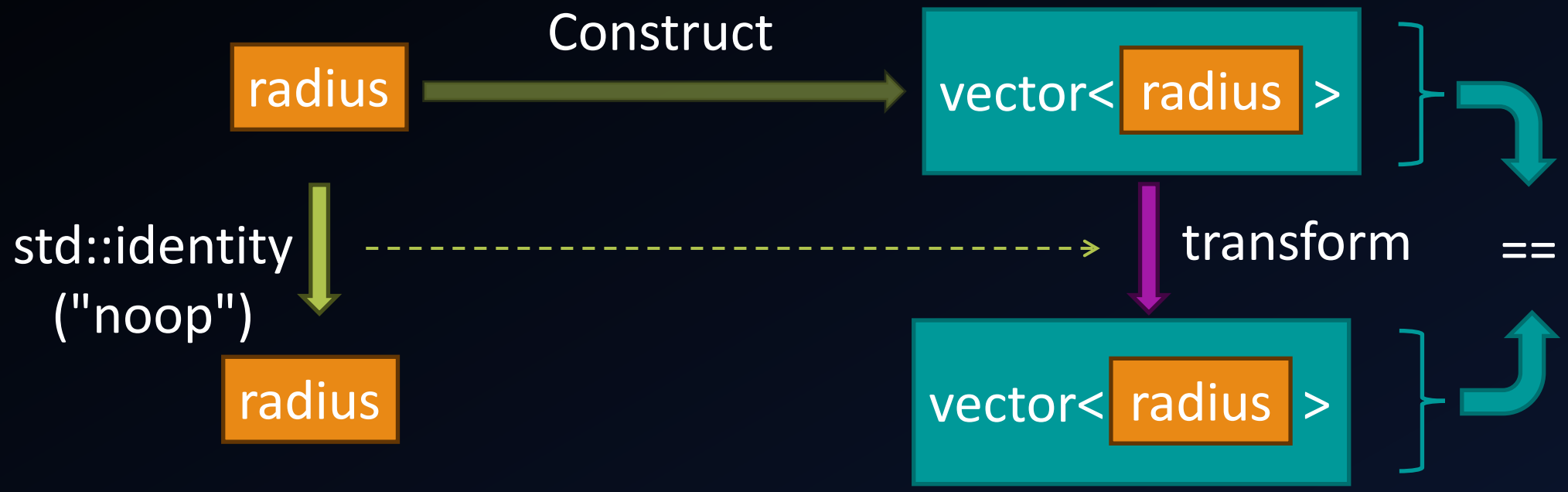


(std::identity simply returns the input parameter)

Rule #2: Identity is Preserved



(std::identity simply returns the input parameter)

A functor

provides a

mapping

that preserves

composition

and

identity

...can be implemented in different ways

...does not have to be an object

...does not have to hold a value

A Functor with a Twist

STD::RANGES::VIEWS

A Look Back at our Classic Vector Example

```
double calcArea(double radius);
string formatArea(double area);

string foo1(double radius)
{
   return formatArea(calcArea(radius));
}

vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}
```

https://godbolt.org/z/9er1Yq9or

Using std::views::transform

```
vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}

vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

It's a Functor!

```
vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}

vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

It's a Functor!

```
vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}

vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);

   // {"2.25", "4", "6.25"}
   //...
}
```

Input

Callable

https://godbolt.org/z/9er1Yq9or

It's a Functor!

```
vector<string> fooVec(vector<double> vecRadii)
{
   vector<string> vecOutput;
   for(const double& radius : vecRadius)
   {
      resultVec.push_back(formatArea(calcArea(radius)));
   }
   return vecOutput;
}

vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

The Pipe to the Rescue

```
vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}

vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

The Pipe to the Rescue

```
vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}

vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

The Pipe to the Rescue

```
vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}

vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(radii,calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

The Pipe to the Rescue

```
vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}

vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

The Pipe to the Rescue

```
vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   //...
}

vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
               | views::transform(calcArea)
               | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```

https://godbolt.org/z/9er1Yq9or

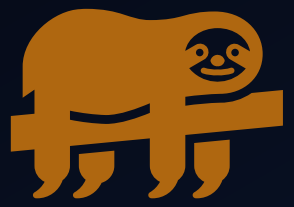
What do we Return?

```
vector<string> fooView(vector<double> vecRadii)
{
   auto output = views::transform(views::transform(radii,calcArea),
                                  formatArea);
   // {"2.25", "4", "6.25"}
   // ...
}

vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
               | views::transform(calcArea)
               | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   // return...?
}
```

What Type is 'output'?

```
vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   //...
}
```



'output' is not the result data
'output' is a view
(with building instructions)

views
do not own
the source data

https://godbolt.org/z/9er1Yq9or

What Type is 'output'?

```
class std::ranges::transform_view
  <class std::ranges::transform_view
    <class std::ranges::ref_view
      <class std::vector
        <double,class std::allocator<double>>
      >,double (__cdecl*)(double)
    >,
  class std::basic_string
    <char,struct std::char_traits<char>,
      class std::allocator<char>
    > (__cdecl*)(double)
  >
```

auto

Returning the View

```
inline auto fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   return output;
}
```

Not a template function!
inline manually!

Returning a Container

```
vector<string> fooPipe(vector<double> vecRadii)
{
   auto output = radii
                 | views::transform(calcArea)
                 | views::transform(formatArea);
   // {"2.25", "4", "6.25"}
   ranges::to<vector<string>>(output);
}
```

Views...

...are building instrcuctions, not results

...typically do not own the source data

...are used with 'auto'

...evaluate lazily

It's a Trap!

```
struct CEntry {
   int m_X{};
   int m_Y{};
   string m_Text{};
};

CEntry getNearestEntry(const int x) {...}

auto v = vector{1,3,7};

auto strings = v
   | views::transform(getNearestEntry)
   | views::transform(&CEntry::m_Text);

printOutput(strings);
```

It's a Trap!

```
struct CEntry {
   int m_X{};
   int m_Y{};
   string m_Text{};
};

CEntry getNearestEntry(const int x) {...}

auto v = vector{1,3,7};

auto strings = v
   | views::transform(getNearestEntry)
   | views::transform(&CEntry::m_Text);

printOutput(strings);
```

It's a Trap!

```
struct CEntry {
   int m_X{};
   int m_Y{};
   string m_Text{};
};

CEntry getNearestEntry(const int x) {...}

auto v = vector{1,3,7};

auto strings = v
   | views::transform(getNearestEntry)
   | views::transform(&CEntry::m_Text);

printOutput(strings);
```

Callables

FEED YOUR FUNCTOR

Callables: Free functions

```
double calcArea      (double radius);
```

```
auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform(calcArea)

    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: (Class) Static Functions

```
class CConv
{
public:
    static double calcAreaStatic(double radius);
    //...
};
//...

auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform(CConv::calcAreaStatic)

    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Inline Lambda

```
auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform([](double radius)
        { return pow(radius, 2.0) * numbers::pi; })
    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Pick Overload with Inline Lambda

```
double  calcArea(const double radius);
int     calcArea(const int value);

auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform([](double radius)
        { return calcArea(radius); })
    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Inject Parameters via Inline Lambda

```
const double power = 3.0;
auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform([power](double value)
        { return pow(value, power); })
    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Pass Object, Call Certain Member Function

```
struct CValue
{
    double getValue() const;
    //...
};

auto vecInput = vector{CValue{1.5},CValue{2.0}};
auto viewOutput = vecInput
    | views::transform([](CValue obj)
        { return obj.getValue(); })
    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Pass Value, Call Member of Certain Object

```
class CConv
{
public:
    double calcAreaMember(const double value);
};
//...

CConv conv;
auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform([&conv](double value)
        { return conv.calcAreaMember(value); })
    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Named Lambda

```
auto calcAreaLambda = [](double value)
{
    return pow(value,2.0);
};


auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform(calcAreaLambda)

    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Function Object

```
struct CCalcArea
{
    double operator()(double radius) const;
};

CCalcArea calcAreaFunctionObject;
auto vecInput = vector{1.5,2.0,2.5};
auto viewOutput = vecInput
    | views::transform(calcAreaFunctionObject)

    | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: std::function

```
#include <functional>

function<double(double)> fAnyFuncDblInDblRet {calcArea};

//...
// Function could be a passed parameter, adding flexibility


    auto vecInput = vector{1.5,2.0,2.5};
    auto viewOutput = vecInput
        | views::transform(fAnyFuncDblInDblRet)

        | //...
```

https://godbolt.org/z/bcEYGYcK3

Callables: Template Parameter

```
template<class TCallable>


void foo(TCallable&& fCallable)
{
    auto vecInput = vector{1.5,2.0,2.5};
    auto viewOutput = vecInput
        | views::transform(forward<TCallable>(fCallable))

        | //...
}
```

https://godbolt.org/z/bcEYGYcK3

Callables: Template Parameter

```
template<class TCallable>
    requires invocable<TCallable,double> &&
        is_same_v<double, invoke_result_t<TCallable,double>>
void foo(TCallable&& fCallable)
{
    auto vecInput = vector{1.5,2.0,2.5};
    auto viewOutput = vecInput
        | views::transform(forward<TCallable>(fCallable))

        | //...
}
```

https://godbolt.org/z/bcEYGYcK3

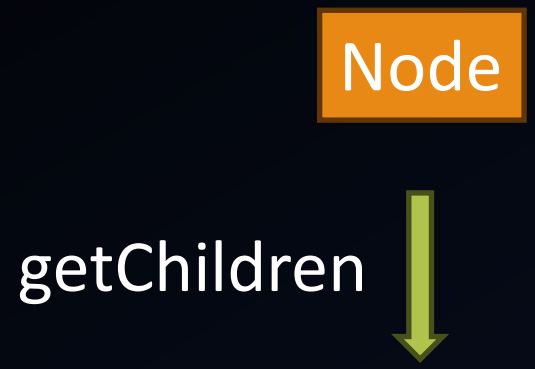
Callables: Summary

Inline Code / Pick Overload	`[](const double& value) { return value * value; }` `[](const double& value) { callFooWithOverloads(value); }`
Extra Param	`[power](const double& value) {return std::pow(value, power);})`
Member of Passed Value	`[](const CValue& obj){return obj.getValue();})`
Pass value to Member	`[&conv](const double& value) {return conv.calcAreaMember(value);}`
Inject callable	`function<double(double)> fCalcArea = calcArea;`

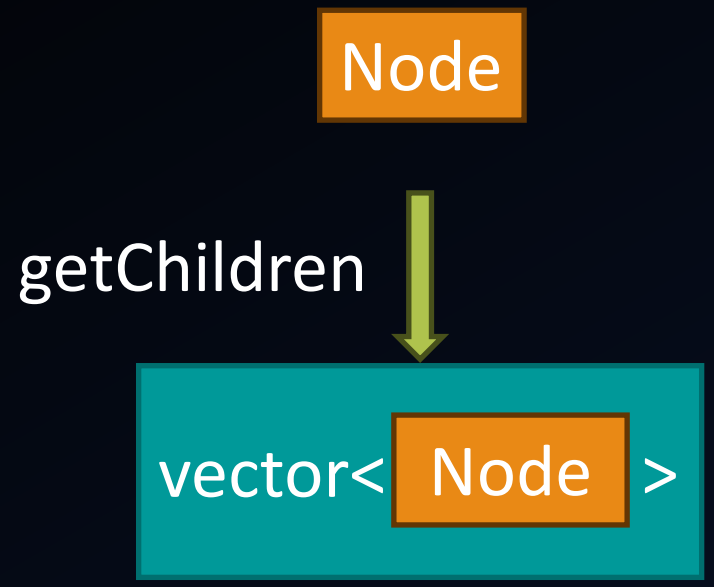
Monads

FUNCTORS+JOIN

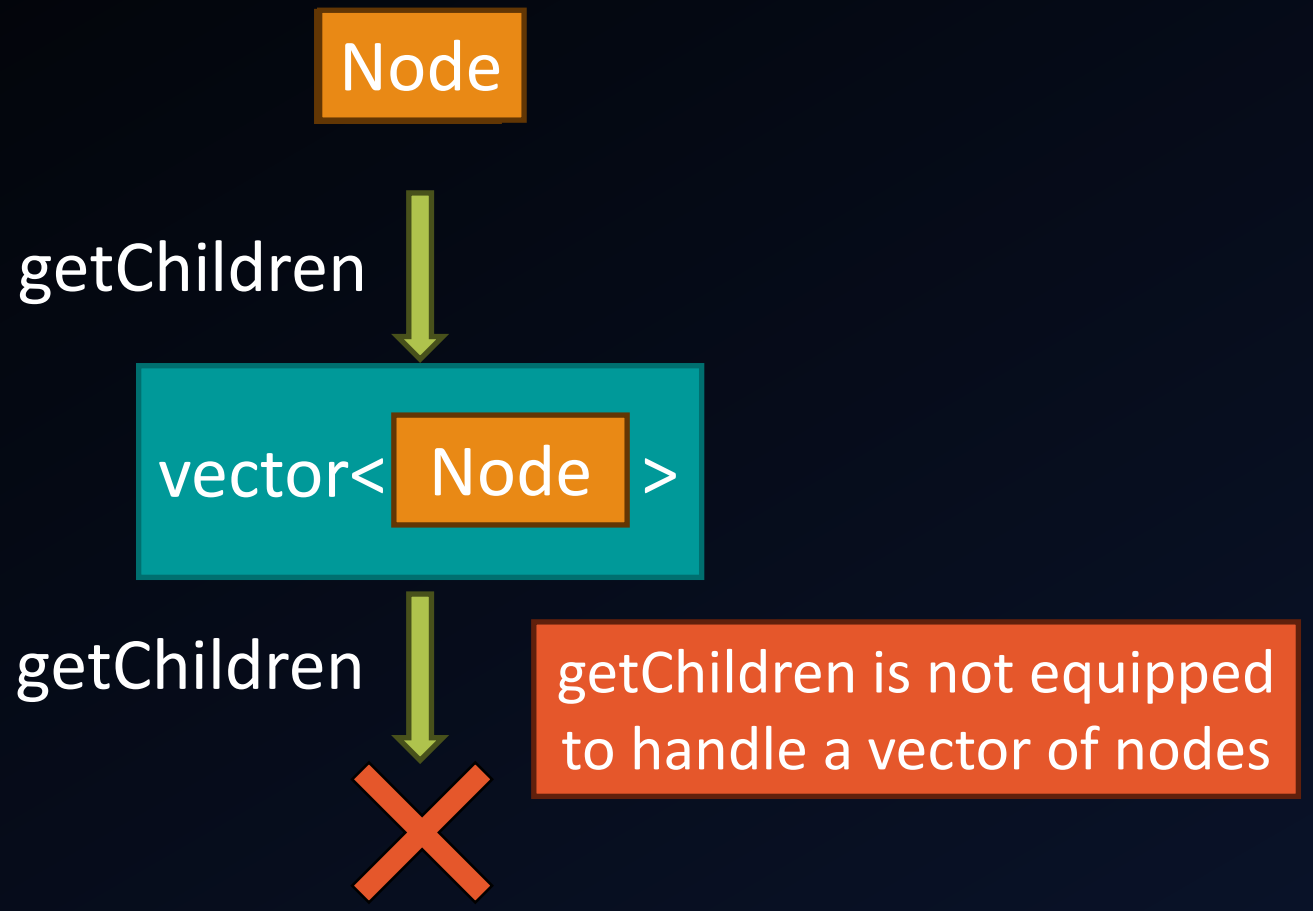
Getting the Children of a Node



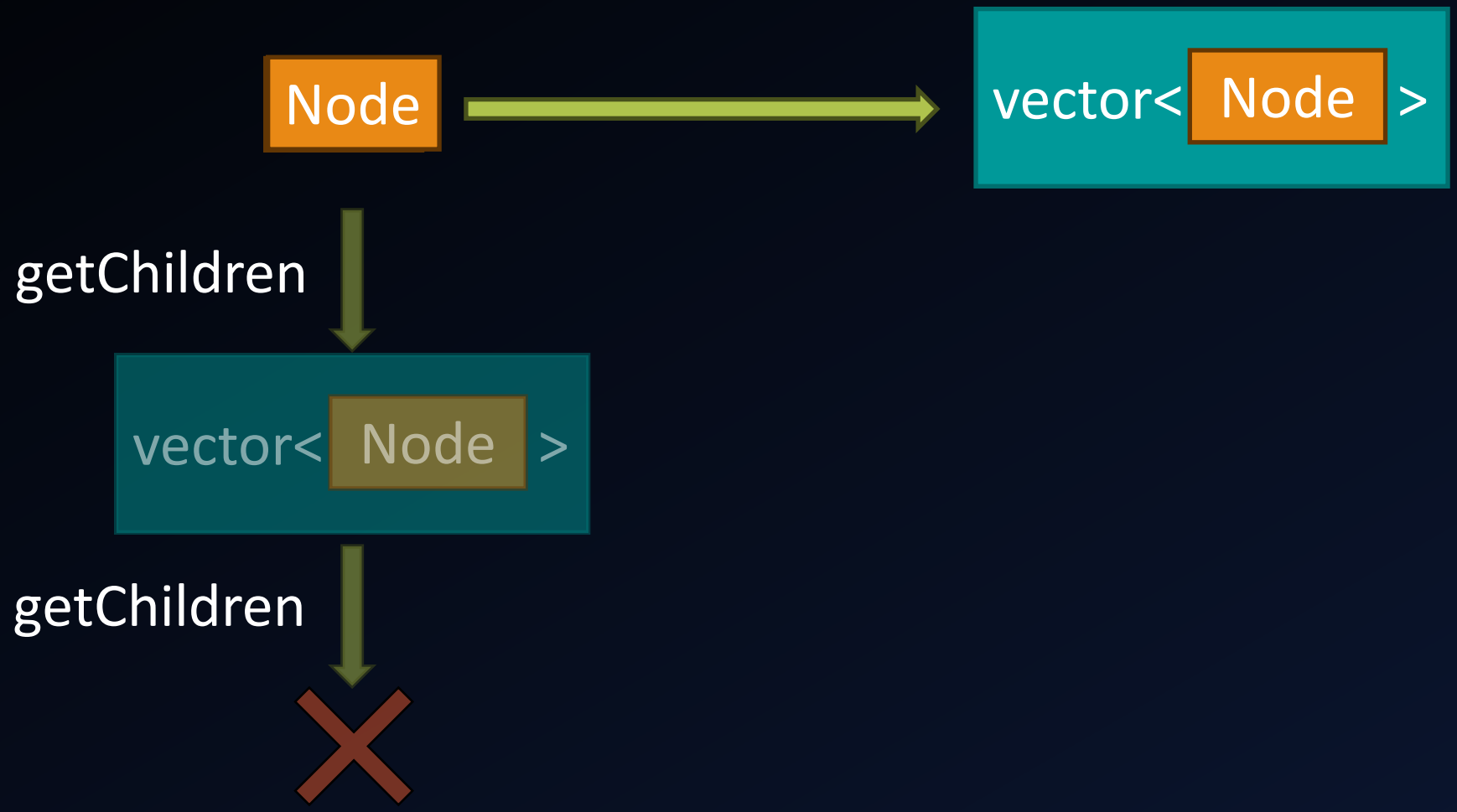
Getting the Children of a Node



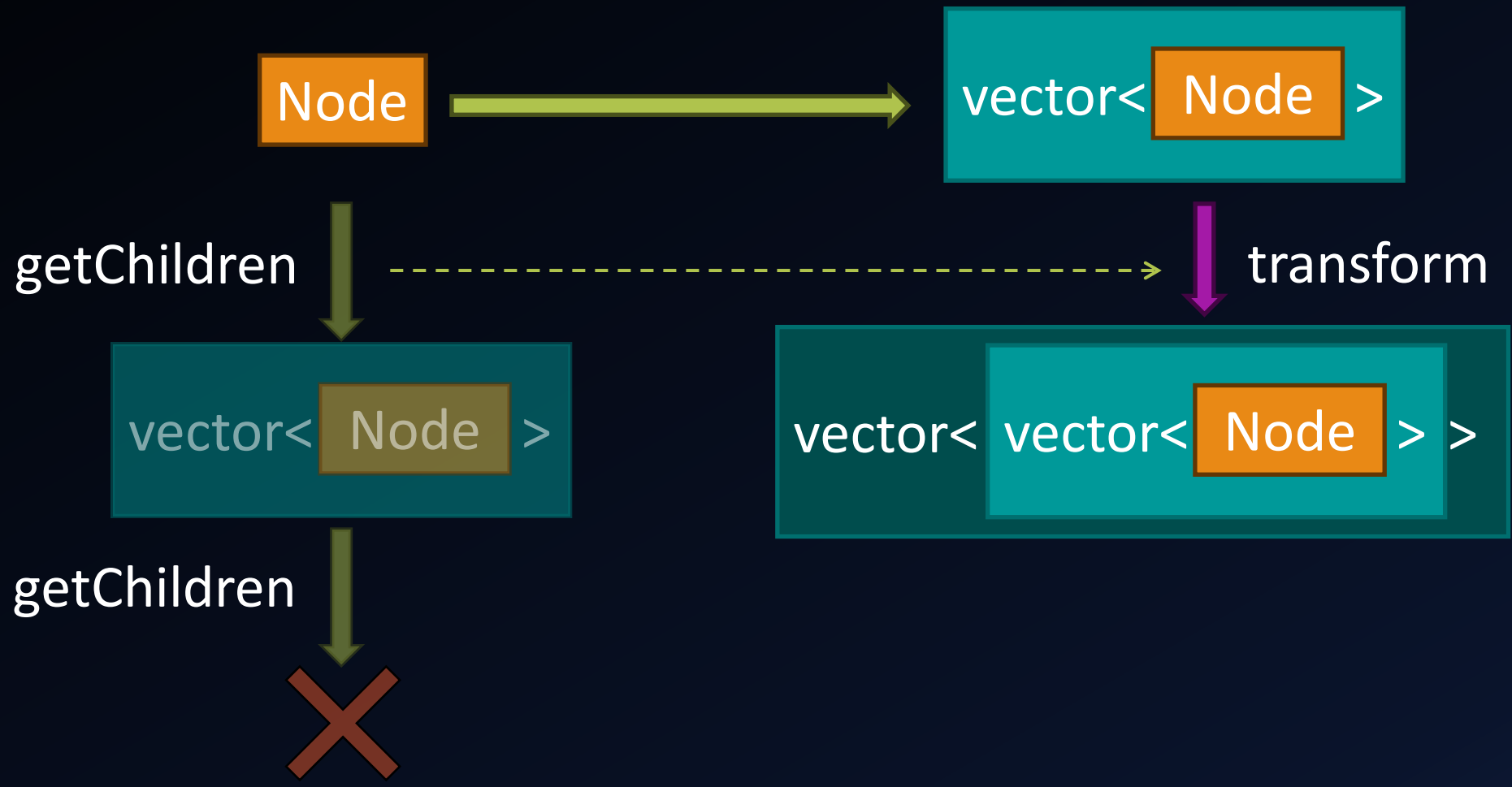
Getting the Children of a Node



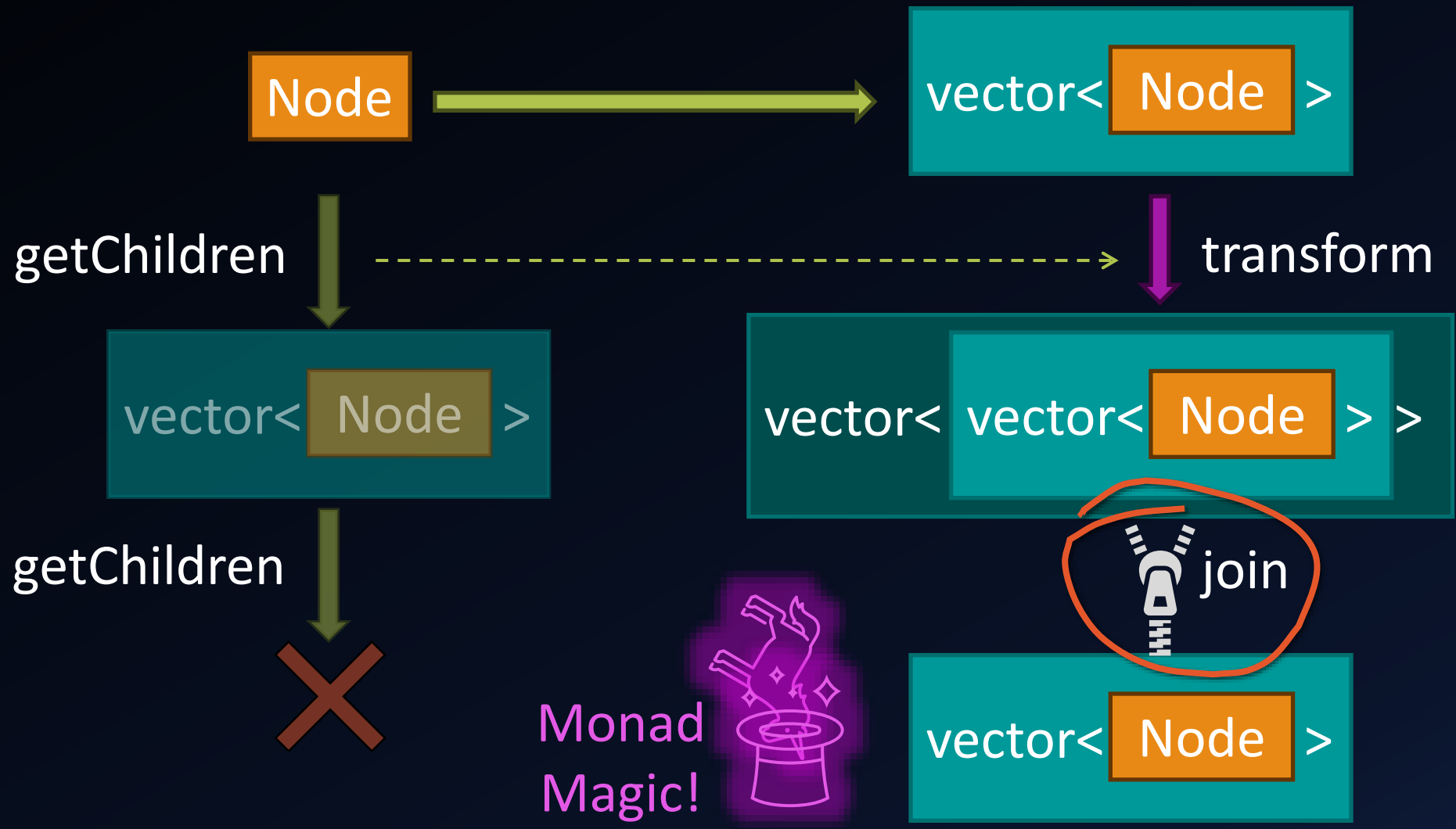
Let's try a Functor Approach



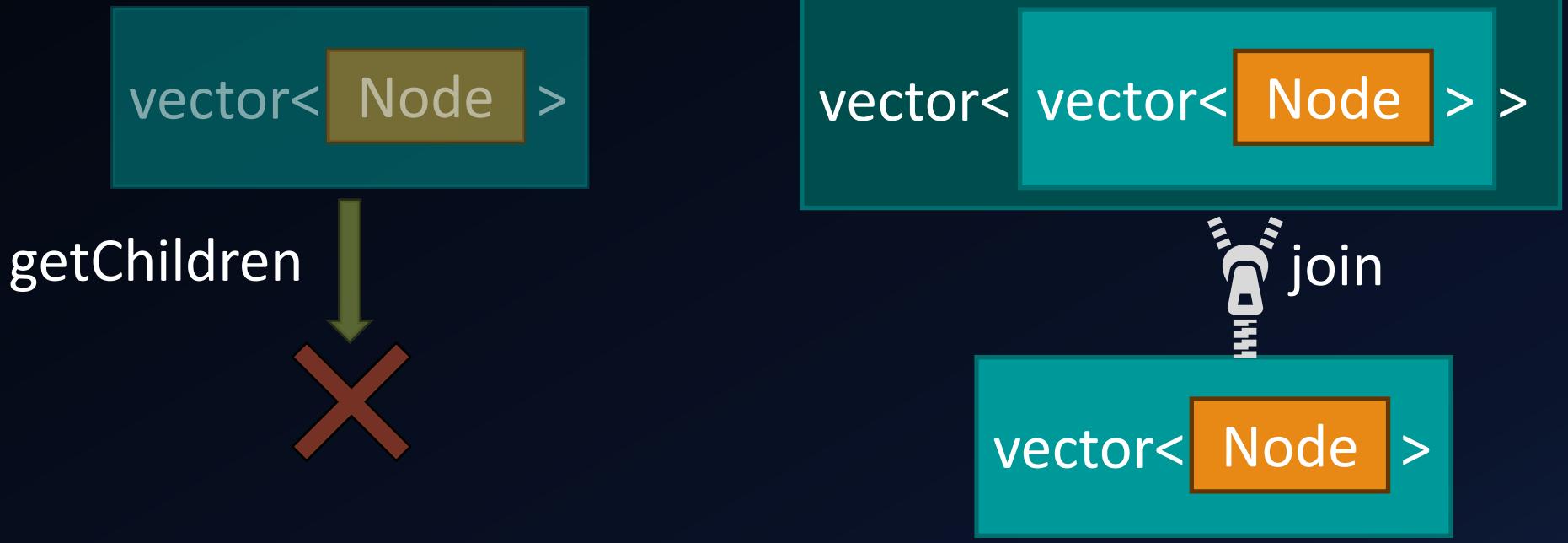
Let's try a Functor Approach



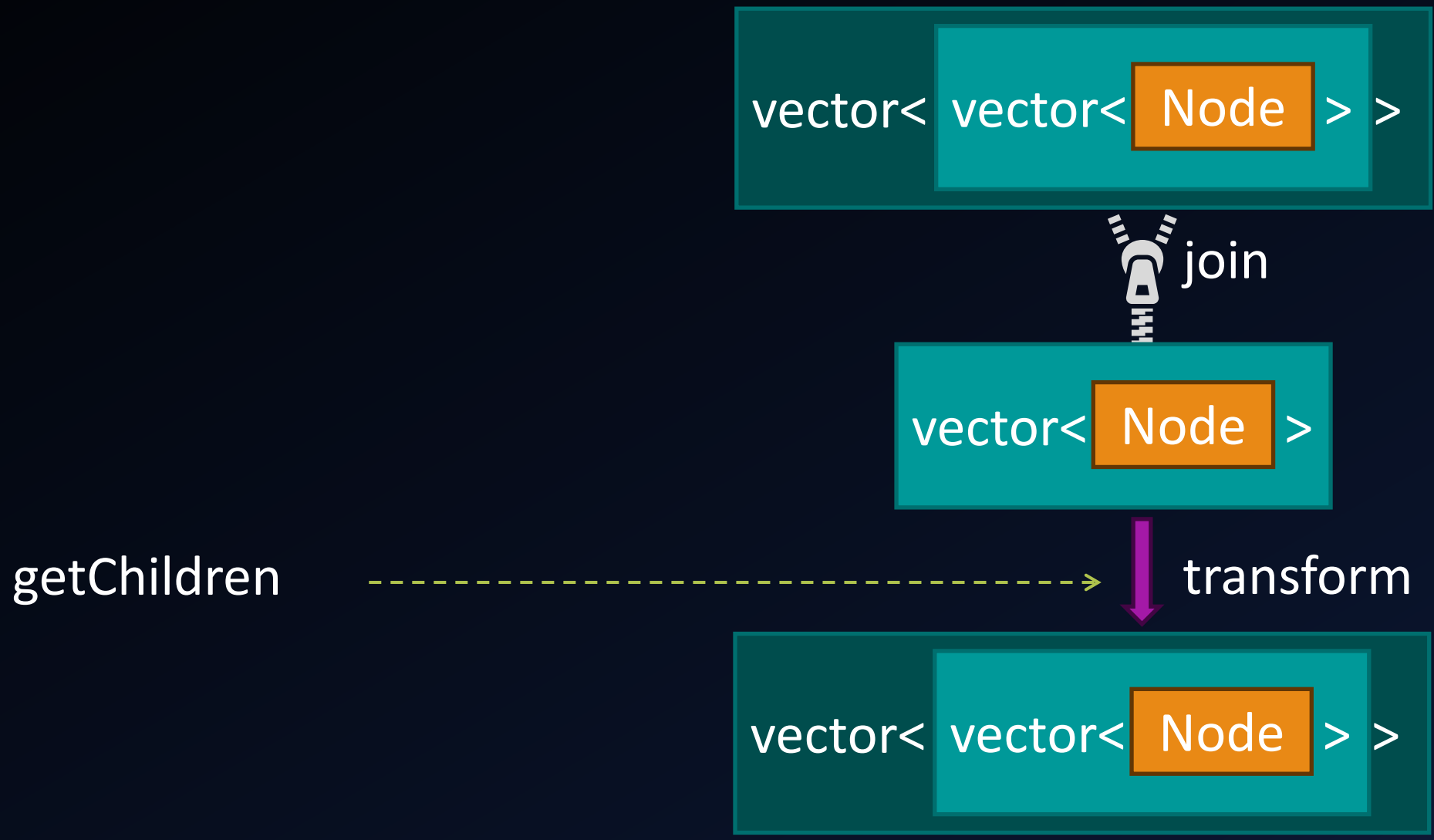
Monad ≈ Functor + Join



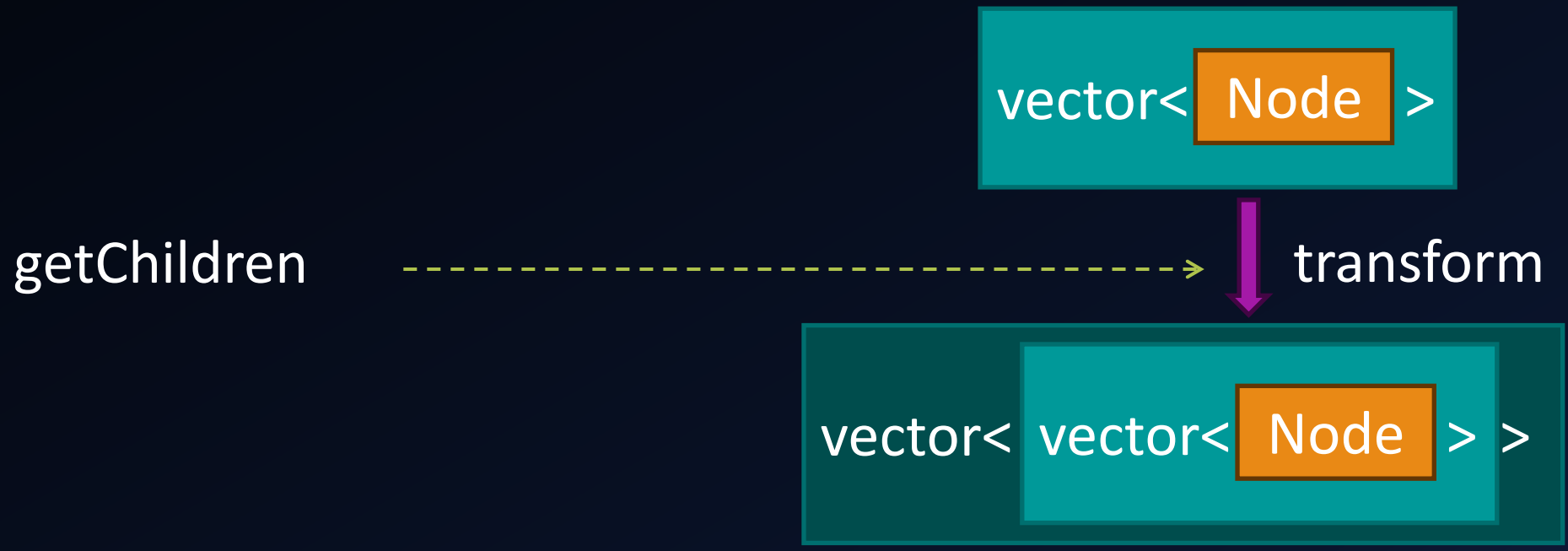
Monad ≈ Functor + Join



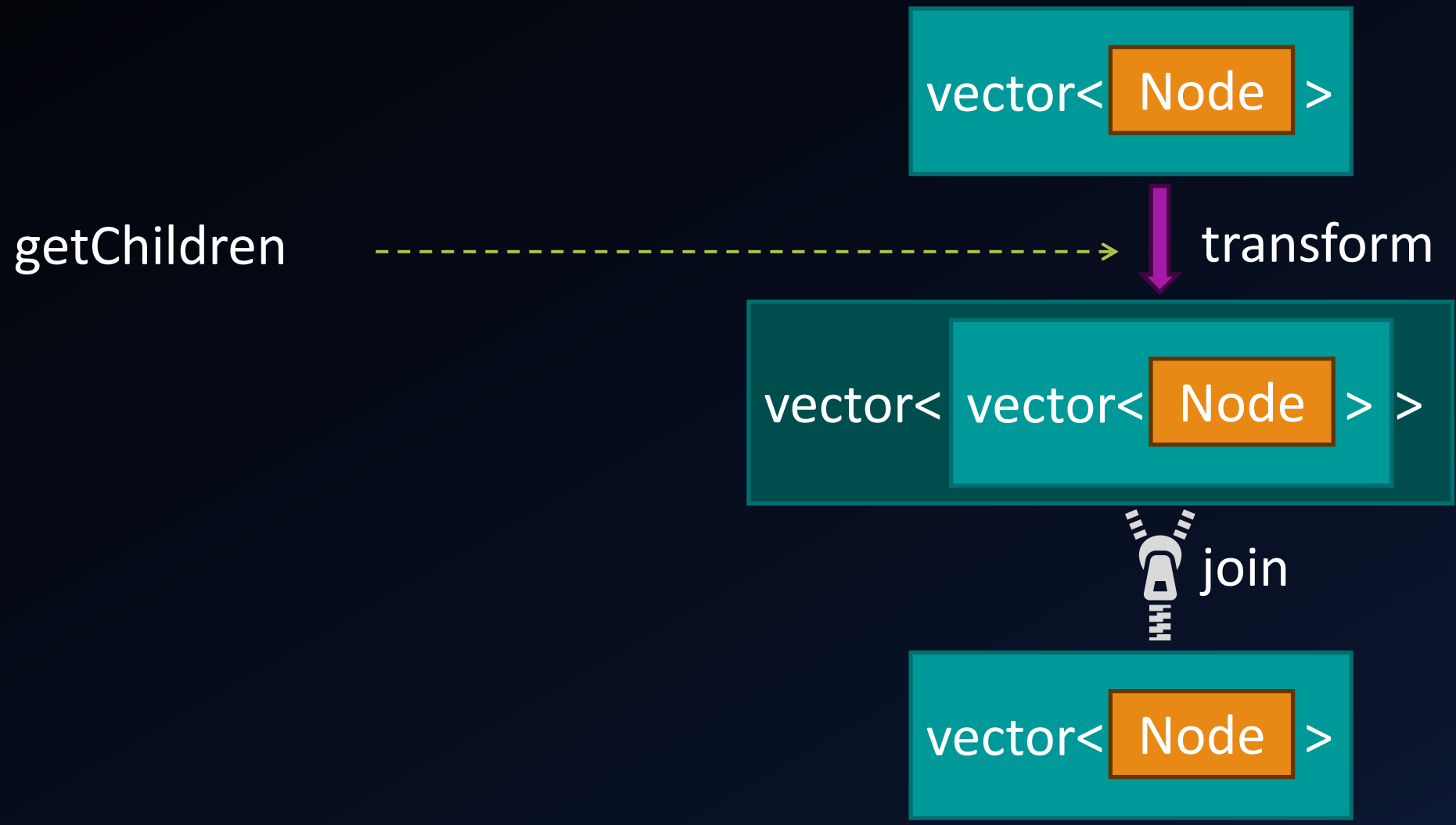
Monad ≈ Functor + Join



Monad ≈ Functor + Join



Monad ≈ Functor + Join



For our purposes a

monad

is a

functor

with the ability to

unwrap

one level of

nesting

Typically cannot unwrap the last level of nesting

Rules about composition and identity still apply

'Transform' and 'Join' are sometimes combined into one function

A Ranges / Views Monad

LET'S JOIN THEM

Printing Diagnostics: Conversion Functions

```
void printDiagnostic(const CDiagnostic& info);

vector<CDiagnostic> compile(const CFile& input);

vector<CFile> getFilesInProject(const CProject& input);
```

https://godbolt.org/z/vbqrTWTeT

Printing Diagnostics: Conversion Functions

```
void printDiagnostic(const CDiagnostic& info);

vector<CDiagnostic> compile(const CFile& input);

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Printing Diagnostics: Conversion Functions

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void printDiagnostic(const CDiagnostic& info);

vector<CDiagnostic> compile(const CFile& input);

vector<CFile> getFilesInProject(const CProject& input);
```

https://godbolt.org/z/vbqrTWTeT

Printing Diagnostics: Classic Loop

```
for(const auto& project : projects)
{
   vector<CFile> files = getFilesInProject(project);

   for(const auto& file : files)
   {
      vector<CDiagnostic> diagnostics = compile(file);
      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}
```

https://godbolt.org/z/vbqrTWTeT

Printing Diagnostics: Classic Loop

```
for(const auto& project : projects)
{
   vector<CFile> files = getFilesInProject(project);

   for(const auto& file : files)
   {
      vector<CDiagnostic> diagnostics = compile(file);
      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}
```

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   for(const auto& file : files)
   {
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      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}
```

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Printing Diagnostics: Classic Loop

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for(const auto& project : projects)
{
   vector<CFile> files = getFilesInProject(project);

   for(const auto& file : files)
   {
      vector<CDiagnostic> diagnostics = compile(file);
      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}
```

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Printing Diagnostics: Classic Loop

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   for(const auto& file : files)
   {
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      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}
```

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Printing Diagnostics: Classic Loop

```
for(const auto& project : projects)
{
   vector<CFile> files = getFilesInProject(project);

   for(const auto& file : files)
   {
      vector<CDiagnostic> diagnostics = compile(file);
      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}
```

https://godbolt.org/z/vbqrTWTeT

Printing Diagnostics: Ranges/View Monad

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

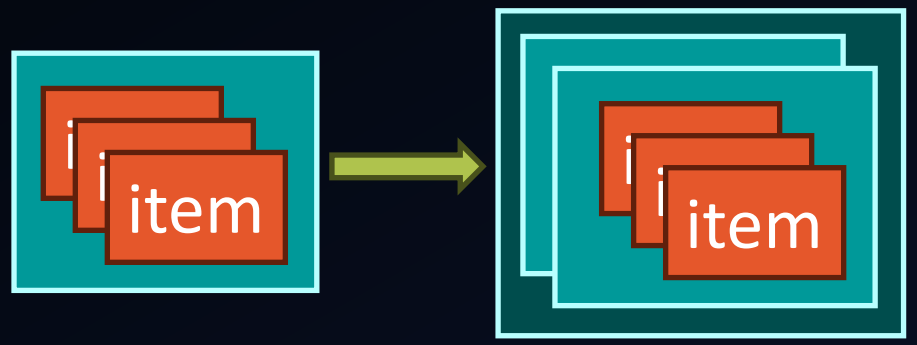
ranges::for_each(diagnostics, printDiagnostic);
```

https://godbolt.org/z/W5dqnavYc

Printing Diagnostics: Ranges/View Monad

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

ranges::for_each(diagnostics, printDiagnostic);
```



https://godbolt.org/z/W5dqnavYc

Printing Diagnostics: Ranges/View Monad

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

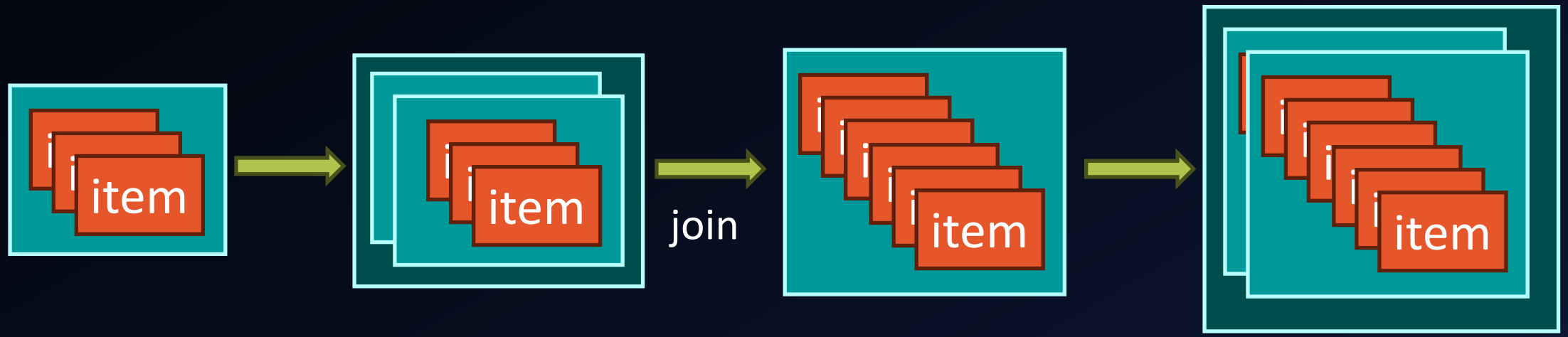
ranges::for_each(diagnostics, printDiagnostic);
```

https://godbolt.org/z/W5dqnavYc

Printing Diagnostics: Ranges/View Monad

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

ranges::for_each(diagnostics, printDiagnostic);
```



https://godbolt.org/z/W5dqnavYc

Printing Diagnostics: Ranges/View Monad

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

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```

https://godbolt.org/z/W5dqnavYc

Printing Diagnostics: Ranges/View Monad

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

ranges::for_each(diagnostics, printDiagnostic);
```

https://godbolt.org/z/W5dqnavYc

Printing Diagnostics: Code Comparison

```
for(const auto& project : projects)
{
   vector<CFile> files = getFilesInProject(project);
   for(const auto& file : files)
   {
      vector<CDiagnostic> diagnostics = compile(file);
      for(const auto& diagnostic : diagnostics)
      {
         printDiagnostic(diagnostic);
      }
   }
}

auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

ranges::for_each(diagnostics, printDiagnostic);
```

Pure Functions

AVOIDING TRAPS

A View of Multiplied Numbers

```
inline auto getMultipliedView(auto&& input, int multiplier)
{
   auto fMultiply = [&](const int number)
      {
         return number * multiplier;
      };

   return views::transform(input, fMultiply);
}

void test()
{
   const auto input = vector{2,4,6};
   auto multipliedView = getMultipliedView(input, 2);
   // Print output
}
```

https://godbolt.org/z/9xbaY6hGe

A View of Multiplied Numbers

```
inline auto getMultipliedView(auto&& input, int multiplier)
{
   auto fMultiply = [&](const int number)
      {
         return number * multiplier;
      };

   return views::transform(input, fMultiply);
}

void test()
{
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}

void test()
{
   const auto input = vector{2,4,6};
   auto multipliedView = getMultipliedView(input, 2);
   // Print output
}
```

```
Starting project...
1587538992
-1119889312
467649680
```

https://godbolt.org/z/9xbaY6hGe

An Unexpected Result

```
inline auto getMultipliedView(auto&& input, int multiplier)
{
   auto fMultiply = [&](const int number)
      {
         return number * multiplier;
      };

   return views::transform(input, fMultiply);
}

void test()
{
   const auto input = vector{2,4,6};
   auto multipliedView = getMultipliedView(input, 2);
   // Print output
}
```

https://godbolt.org/z/9xbaY6hGe

The Functor (or Monad) Controls...

...**when** your functions get called

...**how often** your functions get called

...**in what context** your functions get called

How to Avoid Misuse of Functions?

READ THE FINE PRINT

USE PURE FUNCTIONS

How to Avoid Misuse of Functions?

READ THE FINE PRINT

USE PURE FUNCTIONS

What is a Pure Function?

Same Result
for
Same Input

No Side Effects

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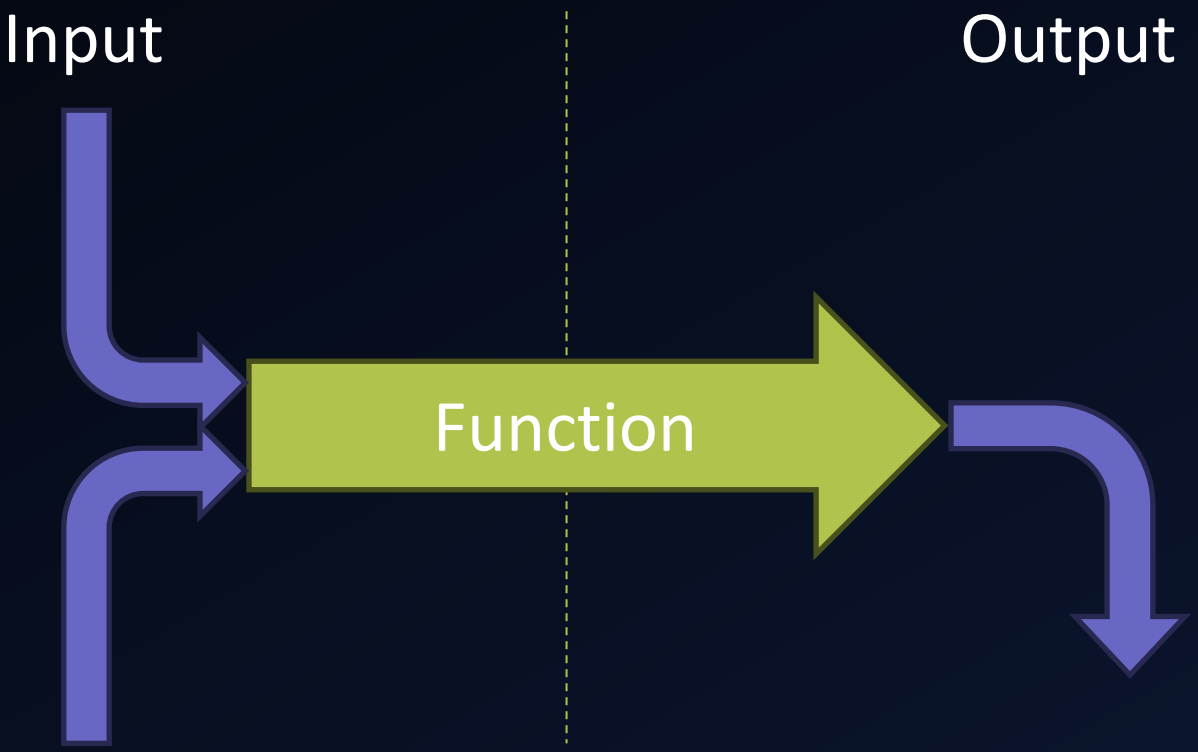

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Same Result
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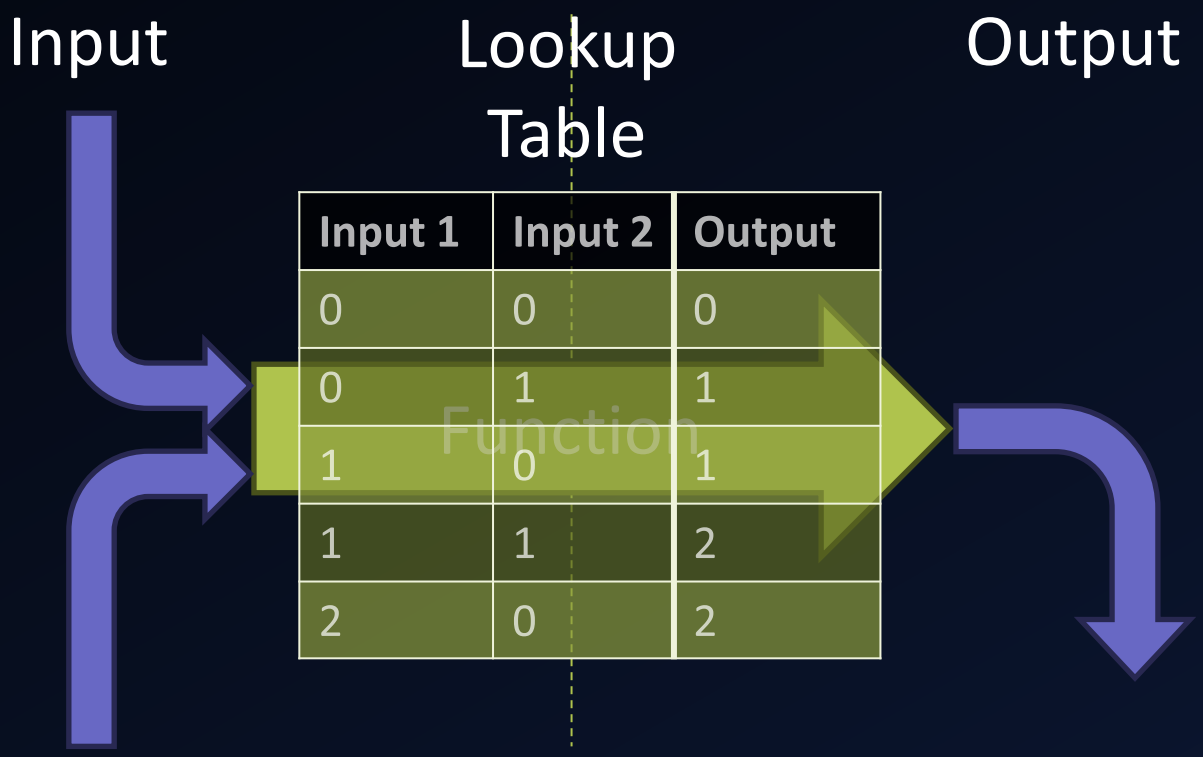
No Side Effects

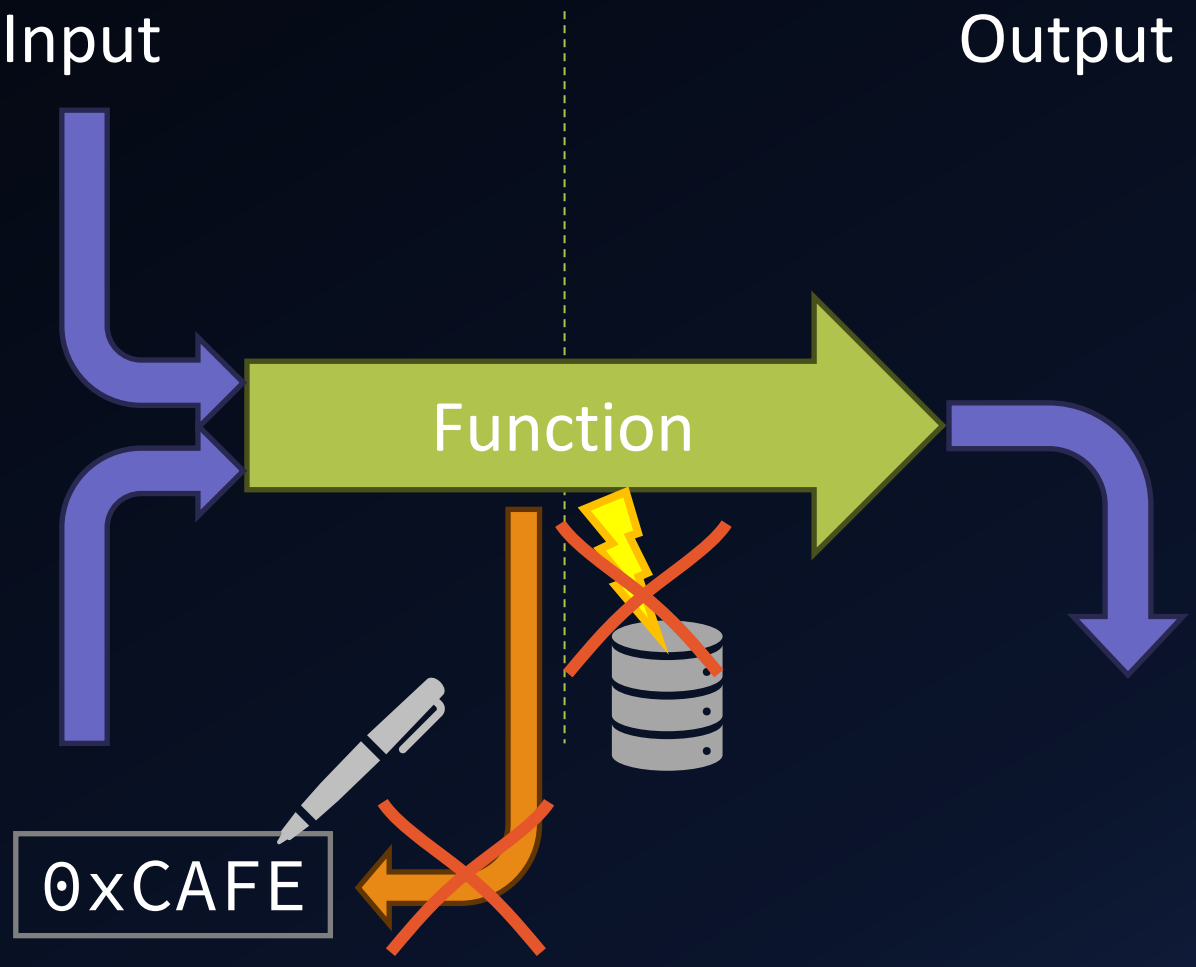


Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	2
2	0	2

What is a Pure Function?

Same Result
for
Same Input

No Side Effects



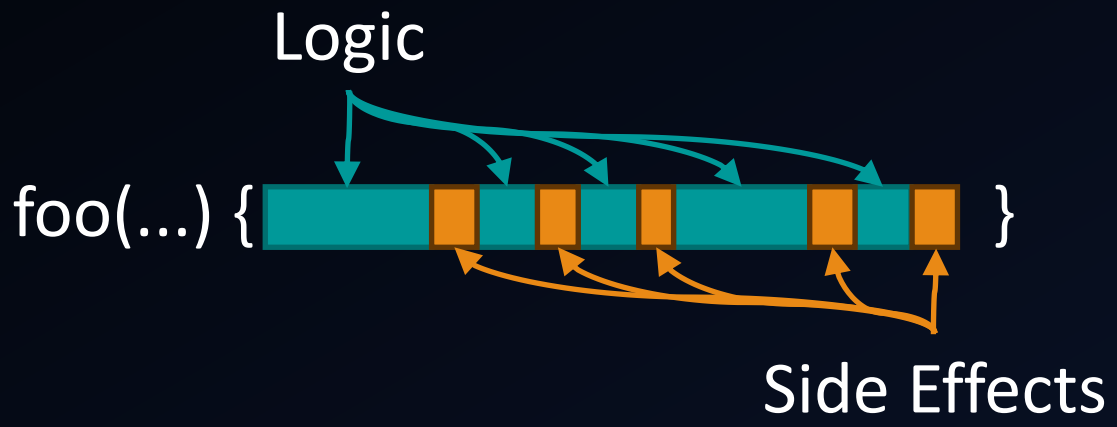
Advantages of Pure Functions

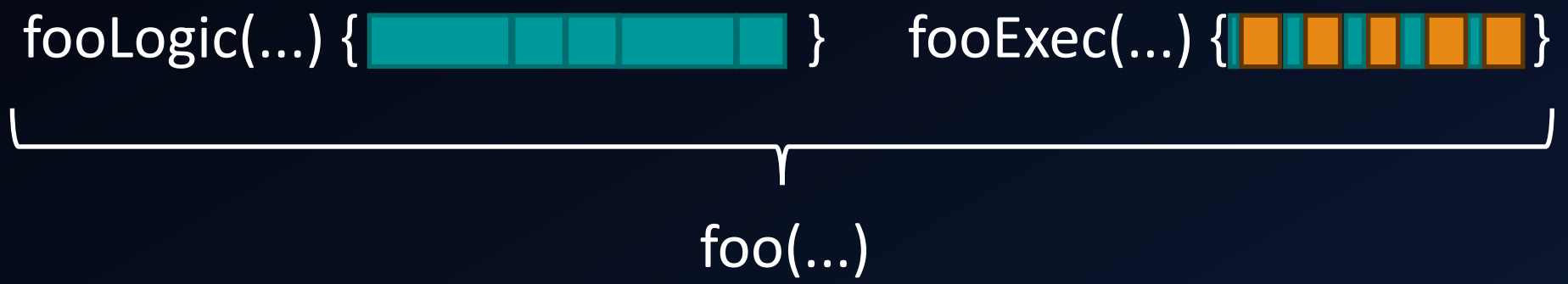
Easy to reason about

Easy to unit test

Thread-safe

Pure Functions: Useful Beyond Functors and Monads





Quiz Time! – Which Function is Pure?

Function	Pure?	Notes
max(int,int)		

Quiz Time! – Which Function is Pure?

Function	Pure?	Notes
max(int,int)	Yes	
fill		

Quiz Time! – Which Function is Pure?

Function	Pure?	Notes
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fill	No	Side effects: Operates on passed iterators
chrono::system_clock::now		

Quiz Time! – Which Function is Pure?

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chrono::system_clock::now	No	Different results: External input
std::sin(double)		

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std::sin(double)	No*)	Different results: Rounding mode may change
std::abs(int)		

Quiz Time! – Which Function is Pure?

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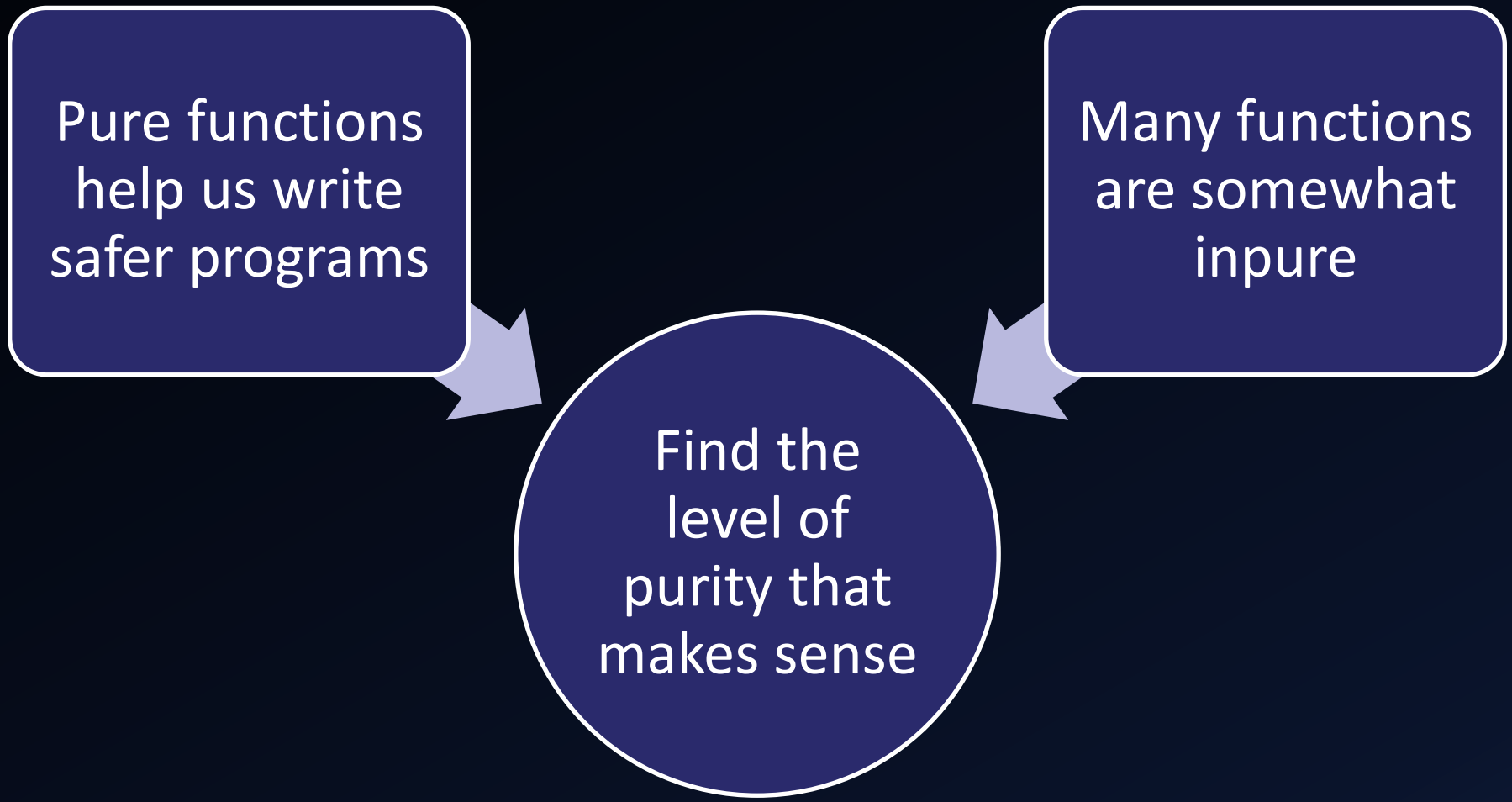
chrono::system_clock::now	No	Different results: External input
std::sin(double)	No*)	Different results: Rounding mode may change
std::abs(int)	?	UB on -INT_MIN (may depend on platform)
std::any_of		

Quiz Time! – Which Function is Pure?

Function	Pure?	Notes
max(int,int)	Yes	
fill	No	Side effects: Operates on passed iterators
chrono::system_clock::now	No	Different results: External input
std::sin(double)	No*)	Different results: Rounding mode may change
std::abs(int)	?	UB on -INT_MIN (may depend on platform)
std::any_of	?	Depends on predicate

Pure Functions and Reality



An (Almost) Pure Fix

```
inline auto getMultipliedView(auto&& input, int multiplier)
{
   auto fMultiply = [&](const int number)
      {
         return number * multiplier;
      };

   return views::transform(input, fMultiply);
}

void test()
{
   const auto input = vector{2,4,6};
   auto multipliedView = getMultipliedView(input, 2);
   // Print output
}
```

Not pure
Depends on outside reference

https://godbolt.org/z/9xbaY6hGe

An (Almost) Pure Fix

```
inline auto getMultipliedView(auto&& input, int multiplier)
{
   auto fMultiply = [multiplier](const int number)
      {
         return number * multiplier;
      };

   return views::transform(input, fMultiply);
}

void test()
{
   const auto input = vector{2,4,6};
   auto multipliedView = getMultipliedView(input, 2);
   // Print output
}
```

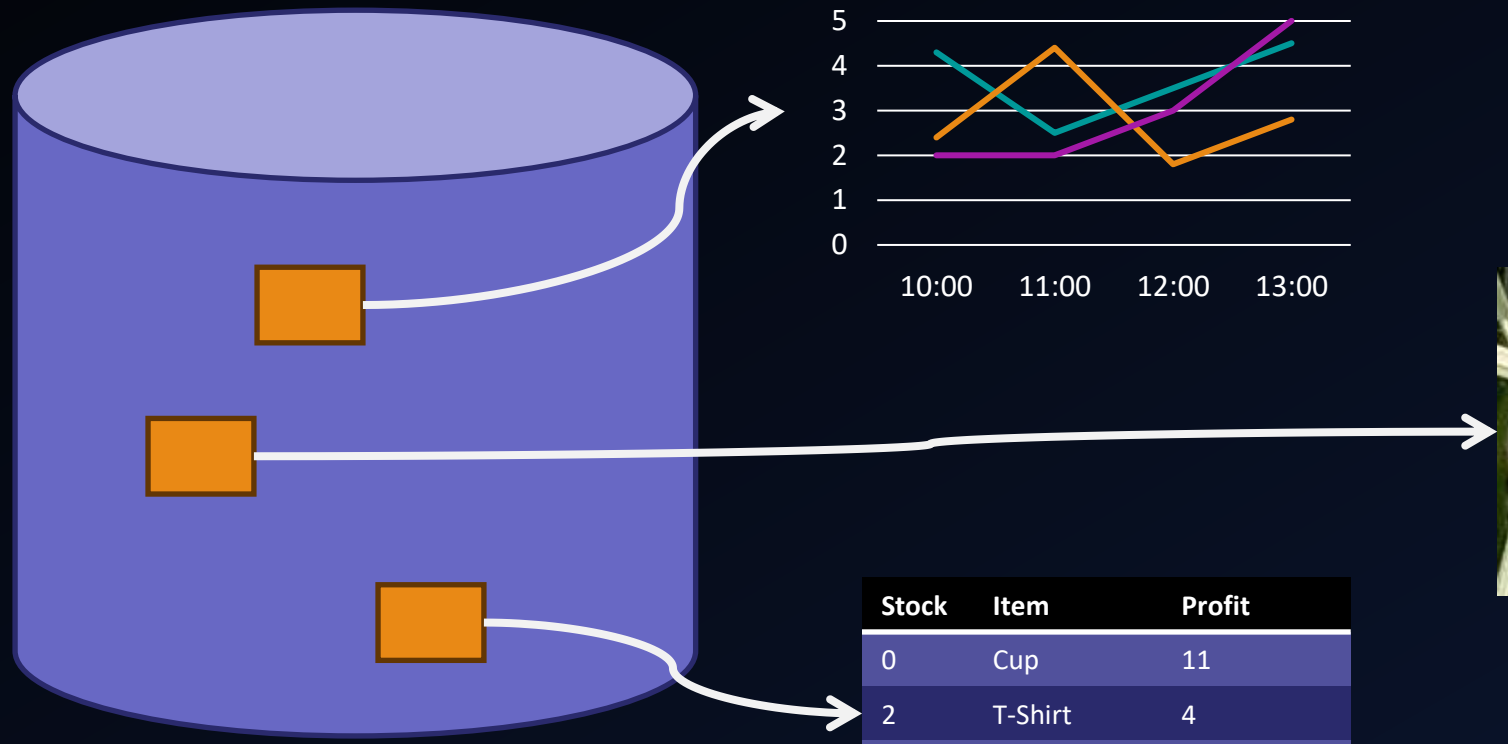
Maybe not really pure,
but pure enough

https://godbolt.org/z/9xbaY6hGe

Handling Failure

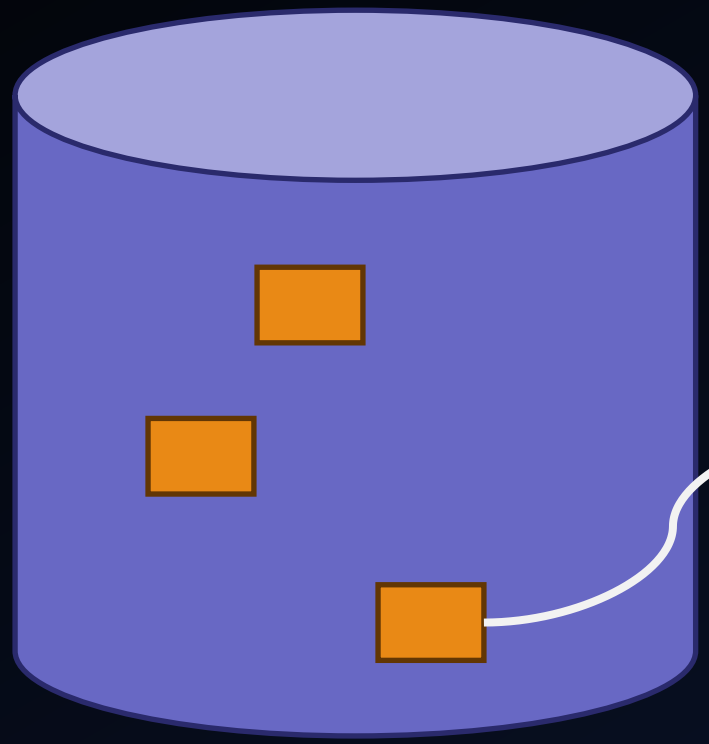
THE OPTIONAL AND EXPECTED MONADS

Handling Failure



Stock	Item	Profit
0	Cup	11
2	T-Shirt	4
0	Poster	16
0	Statuette	-8

Handling Failure



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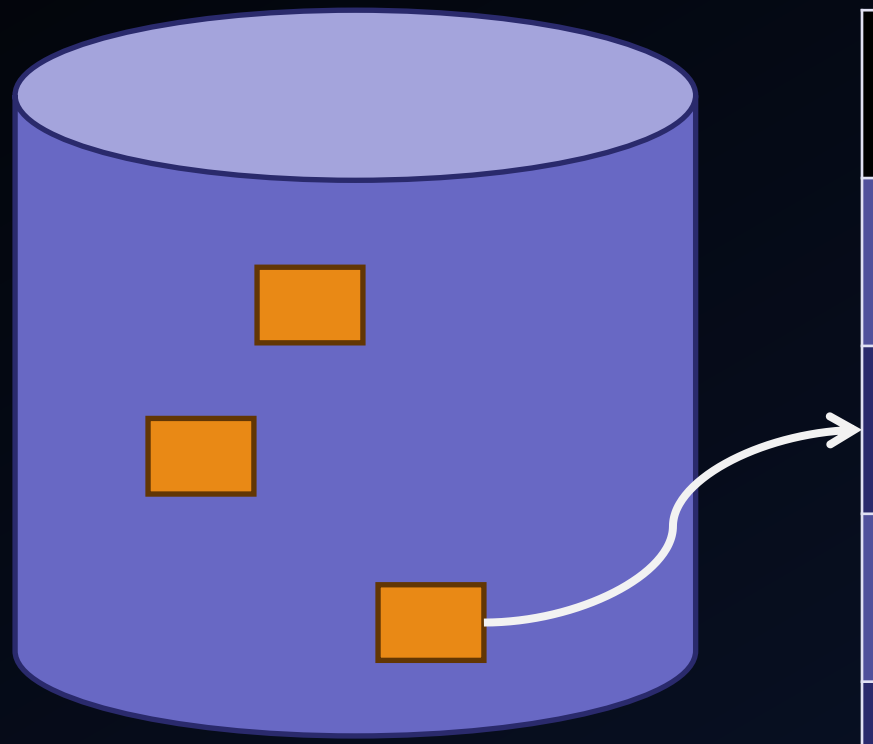

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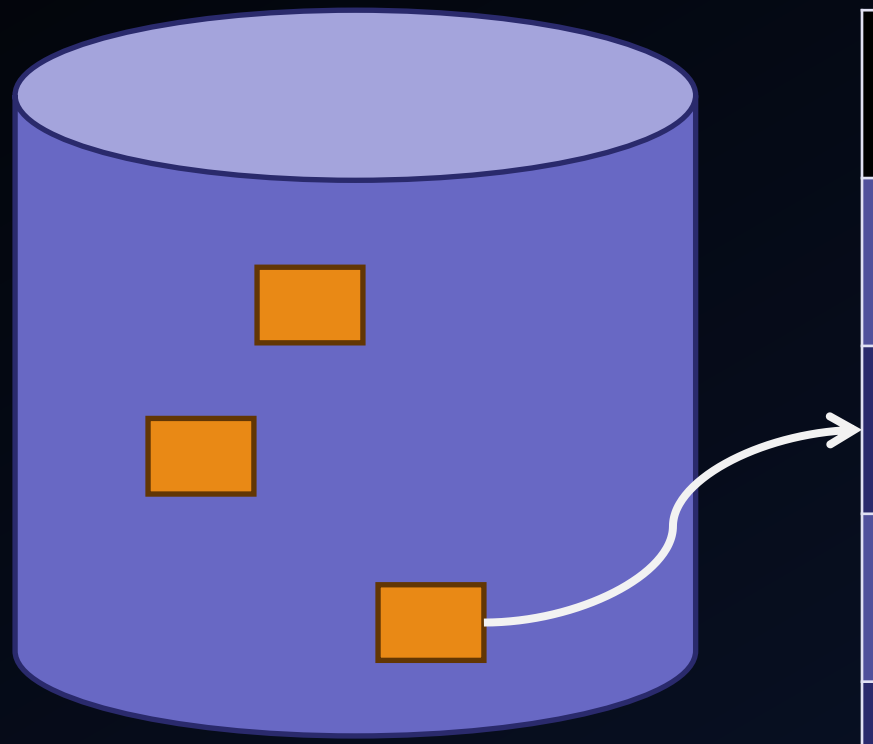
Number?

Handling Failure



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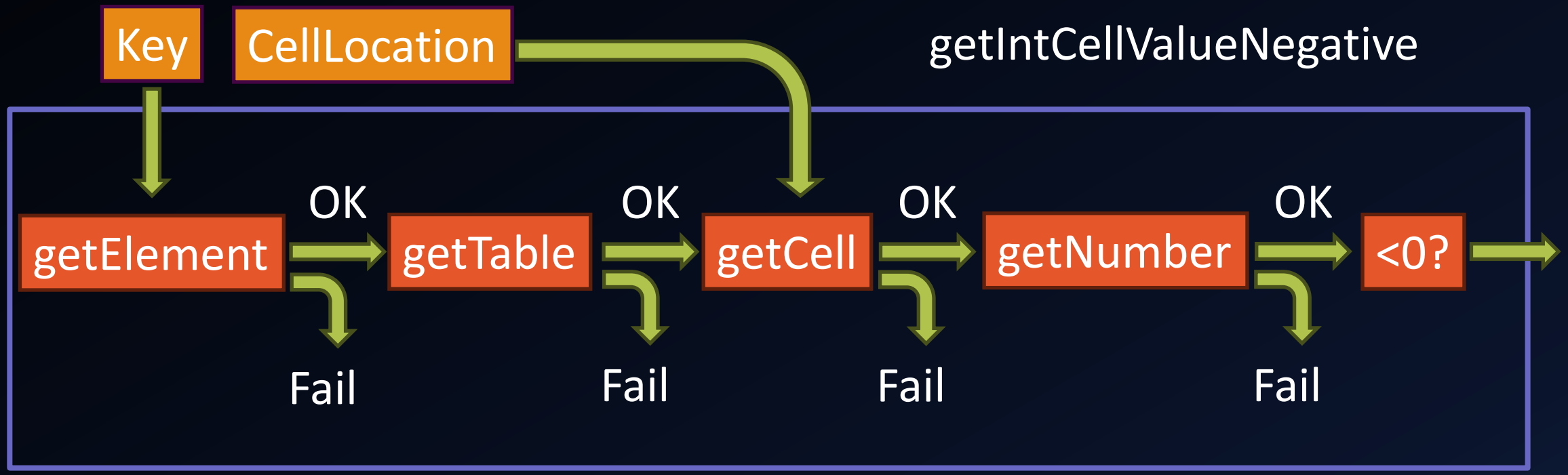
Negative?

Handling Failure



Handling Failure: Classic Way

```
bool getElement(CDb db, CElementKey key, CElement& out);
bool getTable(CElement element, CTable& out);
bool getCell(CTable table, CLocation location CCell& out);
bool getNumericCellValue(CCell cell, int& out);
```

https://godbolt.org/z/fa11WMbdP

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https://godbolt.org/z/fa11WMbdP

Handling Failure: Classic Way

```
bool getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    CElement element;
    if ( ! getElement(db, key, element))          { return false; }

    CTable table;
    if ( ! getTable(element, table))              { return false; }

    CCell cell;
    if ( ! getCell(table, location, cell))        { return false; }

    int value;
    if ( ! getNumericCellValue(cell, value))      { return false; }

    result = (value < 0);
    return true;
}
```

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    int value;
    if ( ! getNumericCellValue(cell, value))      { return false; }

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    return true;
}
```

https://godbolt.org/z/fa11WMbdP

Handling Failure: The Optional Monad

```
bool                getElement(CDb db, CElementKey key, CElement& out);
bool                getTable(CElement element, CTable& out);
bool                getCell(CTable table, CLocation location CCell& out);
bool                getNumericCellValue(CCell cell, int& out);
```

https://godbolt.org/z/rfW6EM68b

Handling Failure: The Optional Monad

```
optional<CElement> getElement(CDb db, CElementKey key);
optional<CTable>   getTable(CElement element);
optional<CCell>    getCell(CTable tableData, CLocation location);
optional<int>      getNumericCellValue(CCell cell);
```

https://godbolt.org/z/rfW6EM68b

Handling Failure: The Optional Monad

```
optional<CElement> getElement(CDb db, CElementKey key);
optional<CTable>   getTable(CElement element);
optional<CCell>    getCell(CTable tableData, CLocation location);
optional<int>      getNumericCellValue(CCell cell);
```

```
{
    //...
    if (/* Key not found */)
    {
        return{}; // or: return nullopt;
     }
    CElement elem = //...
    return elem;
}
```

Handling Failure: The Optional Monad

```
optional<CElement> getElement(CDb db, CElementKey key);
optional<CTable>   getTable(CElement element);
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```

```
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    //...
    if (/* Key not found */)
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    return elem;
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https://godbolt.org/z/rfW6EM68b

Handling Failure: The Optional Monad

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optional<CElement> getElement(CDb db, CElementKey key);
optional<CTable>   getTable(CElement element);
optional<CCell>    getCell(CTable tableData, CLocation location);
optional<int>      getNumericCellValue(CCell cell);
bool               isNegative(int value);
```

https://godbolt.org/z/rfW6EM68b

Handling Failure: The Optional Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
        .and_then(getTable)
        .and_then([location](CTable table)
                  { return getCell(table, location); })
        .and_then(getNumericCellValue)
        .transform(isNegative);
}
```

https://godbolt.org/z/rfW6EM68b

Handling Failure: The Optional Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
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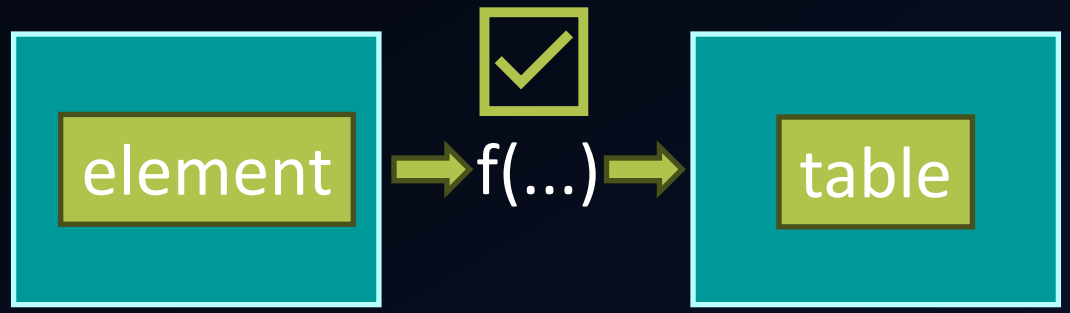

and_then

https://godbolt.org/z/rfW6EM68b

Quiz Time! – What Makes this a Monad?

```
getElement(...) -> optional<CElement>
```

```
getElement(db, key)
          .and_then(getTable)
          //...
```

```
getTable(optional<CElement>) -> optional<CTable>
```

```
auto wrapped = optional<optional<int>>{5};

optional<int> unwrapped =

    wrapped.and_then(identity{});
```

identity

?

Handling Failure: The Optional Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
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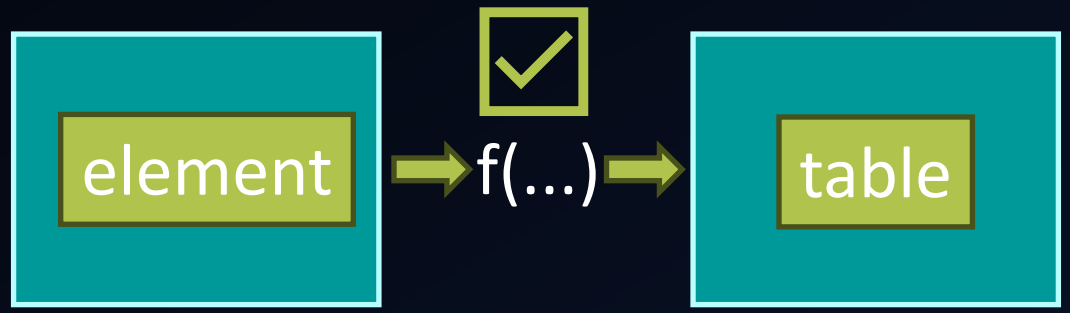
       .and_then(getNumericCellValue)
       .transform(isNegative);
}
```



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       .and_then(getNumericCellValue)
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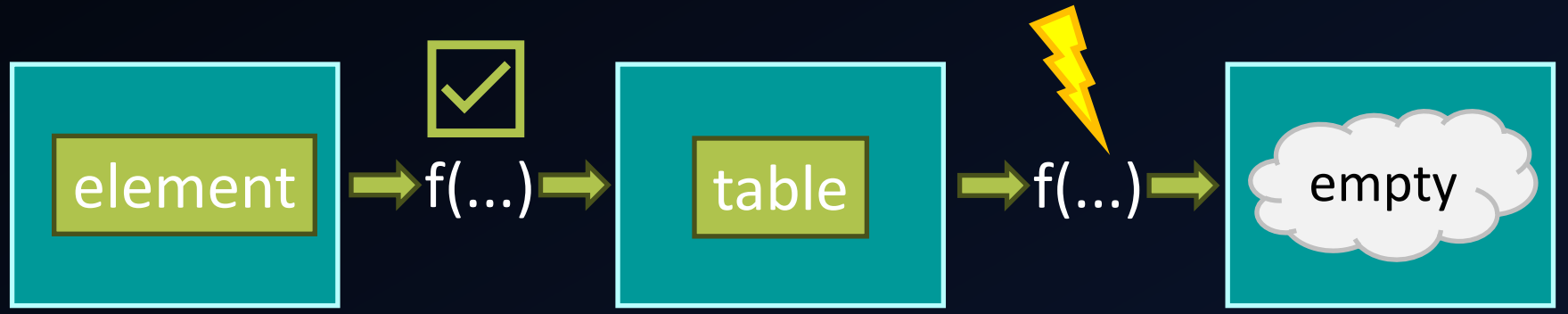
}
```



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}
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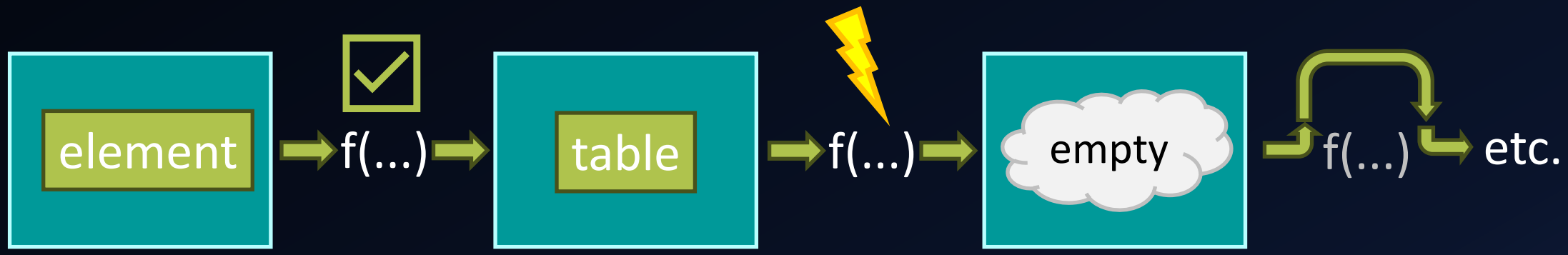

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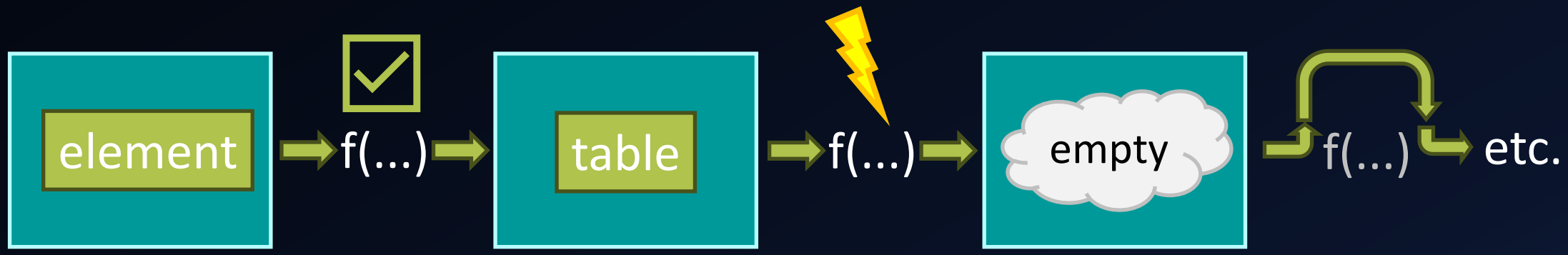
Handling Failure: The Optional Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative);
}
```



https://godbolt.org/z/rfW6EM68b

What can you do with std::optional?

```
optional<int> result = foo();

if (result.has_value())
{
      auto value = result.value();
      //...
}
else
{
      //...
}
```

https://godbolt.org/z/rfW6EM68b

What can you do with std::optional?

```
optional<int> result = foo();

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}
```

https://godbolt.org/z/rfW6EM68b

What can you do with std::optional?

~~optional<int> result = foo();~~

```
if (auto result = foo())
{
      auto value = result.value();
      //...
}
else
{
      //...
}
```

https://godbolt.org/z/rfW6EM68b

What can you do with std::optional?

```
optional<TRet> result = foo();

if (auto result = foo())
{
auto value = foo().value_or(0);
    //...
}
else
{
    //...
}
```

https://godbolt.org/z/rfW6EM68b

Handling Failure: Code Comparison

```
CElement element;
if ( ! getElement(db, key, element))      { return false; }
CTable table;
if ( ! getTable(element, table))          { return false; }
CCell cell;
if ( ! getCell(table, location, cell))    { return false; }
int value;
if ( ! getNumericCellValue(cell, value))  { return false; }
result = (value < 0);
return true;
```

```
return getElement(db, key)
    .and_then(getTable)
    .and_then([location](CTable table)
              { return getCell(table, location); })
    .and_then(getNumericCellValue)
    .transform(isNegative);
```

Catching failure: or_else

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative)
       .or_else(log<bool>);
}
```

https://godbolt.org/z/rfW6EM68b

Catching failure: or_else

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative)
       .or_else(log<bool>);
}
```

```
template<class TRet>
optional<TRet> log();
```

https://godbolt.org/z/rfW6EM68b

Catching failure: Lack of Error Context

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative)
       .or_else(log<bool>);
}
```

No error context!

https://godbolt.org/z/rfW6EM68b

Returning Error State: The Expected Monad

```
optional<CElement> getElement(CDb db, CElementKey key);

optional<CTable> getTable(CElement element);

optional<CCell> getCell(CTable tableData, CLocation location);

optional<int> getNumericCellValue(CCell cell);

bool isNegative(int value);
```

Returning Error State: The Expected Monad

```
expected<CElement,CErr> getElement(CDb db, CElementKey key);
expected<CTable,CErr> getTable(CElement element);
expected<CCell,CErr> getCell(CTable tableData, CLocation location);
expected<int,CErr> getNumericCellValue(CCell cell);
bool isNegative(int value);
```

https://godbolt.org/z/sKGb6qPo9

Returning Error State: The Expected Monad

```
expected<CElement,CErr> getElement(CDb db, CElementKey key);
expected<CTable,CErr> getTable(CElement element);
expected<CCell,CErr> getCell(CTable tableData, CLocation location);
expected<int,CErr> getNumericCellValue(CCell cell);
bool isNegative(int value);
```

```
{
    //...
    if (/* Key not found */)
    {
        return unexpected{CErr("Key not found")};
     }
    CElement elem = //...
    return elem;
}
```

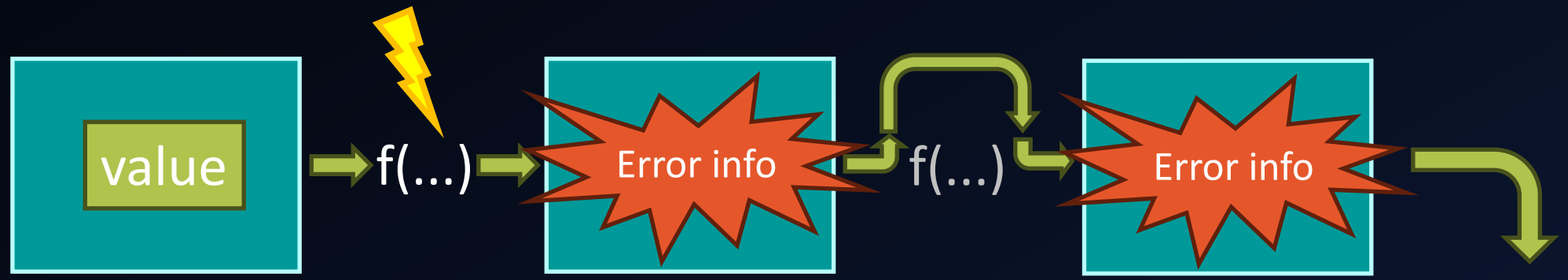
Returning Error State: The Expected Monad

```
expected<CElement,CErr> getElement(CDb db, CElementKey key);
expected<CTable,CErr> getTable(CElement element);
expected<CCell,CErr> getCell(CTable tableData, CLocation location);
expected<int,CErr> getNumericCellValue(CCell cell);
bool isNegative(int value);
```

```
{
    //...
    if (/* Key not found */)
    {
        return unexpected{CErr("Key not found")};
     }
    CElement elem = //...
    return elem;
}
```

Returning Error State: The Expected Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative);
}
```



https://godbolt.org/z/sKGb6qPo9

Returning Error State: The Expected Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative)
       .or_else(log<bool>);
}
```

CErr with context

```
template<class TRet>
expected<TRet,CErr> log(CErr errorInfo);
```

https://godbolt.org/z/sKGb6qPo9

Returning Error State: The Expected Monad

```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative)
       .or_else(log<bool>);
}
```

```
template<class TRet>
expected<TRet,CErr> log(CErr errorInfo);
```

https://godbolt.org/z/sKGb6qPo9

What can do with std::expected?

```
expected<int,CErr> result = foo();

if (result.has_value())
{
     auto value = result.value();
     //...
}
else
{
     auto err = result.error();
     //...
}
```

https://godbolt.org/z/sKGb6qPo9

What can do with std::expected?

```
expected<int,CErr> result = foo();

if (result.has_value())
{
     auto value = result.value();
     //...
}
else
{
     auto err = result.error();
     //...
}
```

https://godbolt.org/z/sKGb6qPo9

What can do with std::expected?

```
expected<int,CErr> result = foo();

if (result.has_value())
{
      auto value = result.value();
      //...
}
else
{
      auto err = result.error();
      //...
}
```

What can do with std::expected?

~~optional<int> result = foo();~~

```
if (auto result = foo())
{
      auto value = result.value();
      //...
}
else
{
      // Cannot access result
}
```

https://godbolt.org/z/sKGb6qPo9

What can do with std::expected?

```
optional<TRet> result = foo();

if (auto result = foo())
{
auto value = foo().value_or(0);
    //...
}
else
{
    //...
}
```

https://godbolt.org/z/sKGb6qPo9

Transforming the Error Type

```
MyError convertCErrToMyErr(CErr errorInfo);

//...

expected<int,CErr> result = foo();

expected<int,MyError> = result.transform_error(convertCErrToMyErr);
```

https://godbolt.org/z/sKGb6qPo9

Transforming the Error Type

```
MyError convertCErrToMyErr(CErr errorInfo);

//...

expected<int,CErr> result = foo();

expected<int,MyError> = result.transform_error(convertCErrToMyErr);
```

https://godbolt.org/z/sKGb6qPo9

Transforming the Error Type

```
MyError convertCErrToMyErr(CErr errorInfo);

//...

expected<int,CErr> result = foo();

expected<int,MyError> = result.transform_error(convertCErrToMyErr);
```

https://godbolt.org/z/sKGb6qPo9

Transforming the Error Type

```
MyError convertCErrToMyErr(CErr errorInfo);

//...

expected<int,CErr> result = foo();

expected<int,MyError> = result.transform_error(convertCErrToMyErr);
```

https://godbolt.org/z/sKGb6qPo9

The Default "Monad"

THE OTHER SIDE OF STD::OPTIONAL

Picking First Success: The Default "Monad"

```
optional<ELanguage> getLanguageFromCommandLine();

optional<ELanguage> getLanguageFromRegistry();

optional<ELanguage> getLanguageFromEnvironment();

//Fallback: ELanguage::English
```

https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

```
optional<ELanguage> getLanguageFromCommandLine();
optional<ELanguage> getLanguageFromRegistry();
optional<ELanguage> getLanguageFromEnvironment();
//Fallback: ELanguage::English
```

https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

```
optional<ELanguage> getLanguageFromCommandLine();
optional<ELanguage> getLanguageFromRegistry();
optional<ELanguage> getLanguageFromEnvironment();
//Fallback: ELanguage::English
```

https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

```
optional<ELanguage> getLanguageFromCommandLine();
optional<ELanguage> getLanguageFromRegistry();
optional<ELanguage> getLanguageFromEnvironment();
//Fallback: ELanguage::English
```

https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

```
optional<ELanguage> getLanguageFromCommandLine();
optional<ELanguage> getLanguageFromRegistry();
optional<ELanguage> getLanguageFromEnvironment();
//Fallback: ELanguage::English
```

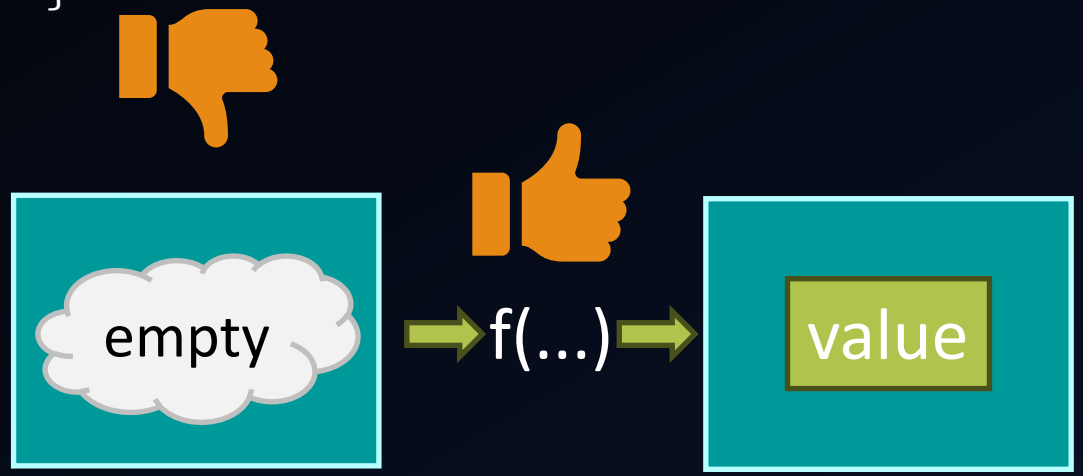
Picking First Success: The Default "Monad"

```
ELanguage getStartupLanguage()
{
    return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
}
```

https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

```
ELanguage getStartupLanguage()
{
    return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
}
```

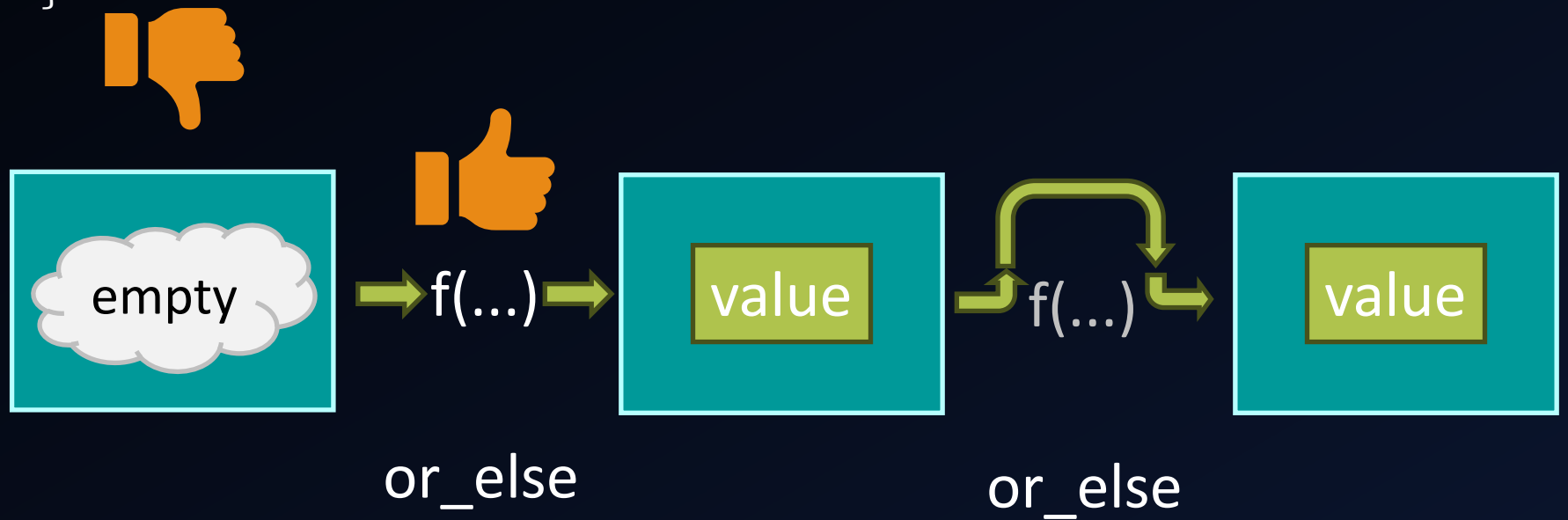


or_else

https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

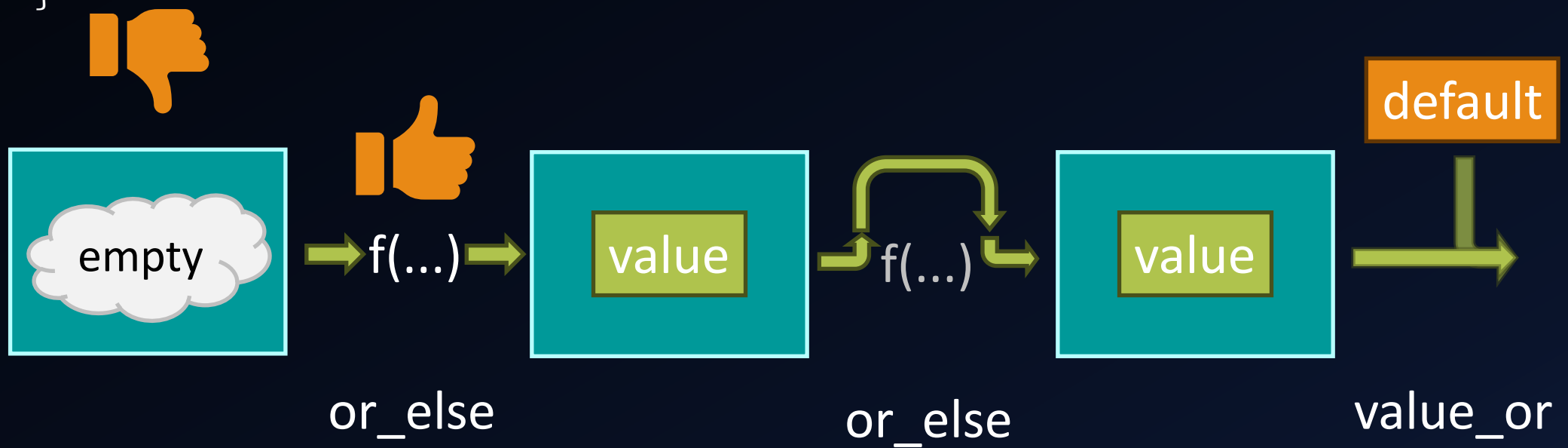
```
ELanguage getStartupLanguage()
{
    return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
}
```



https://godbolt.org/z/zz5coz13T

Picking First Success: The Default "Monad"

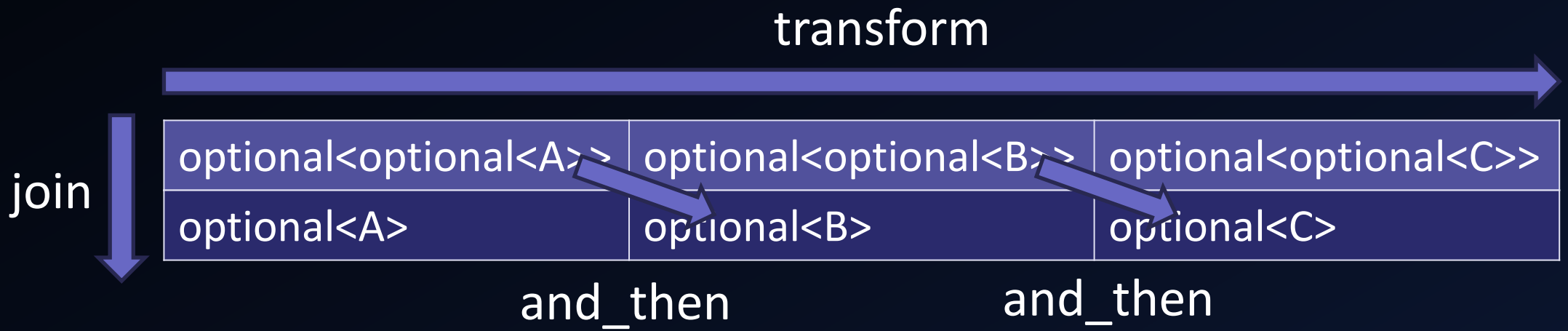
```
ELanguage getStartupLanguage()
{
    return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
}
```



https://godbolt.org/z/zz5coz13T

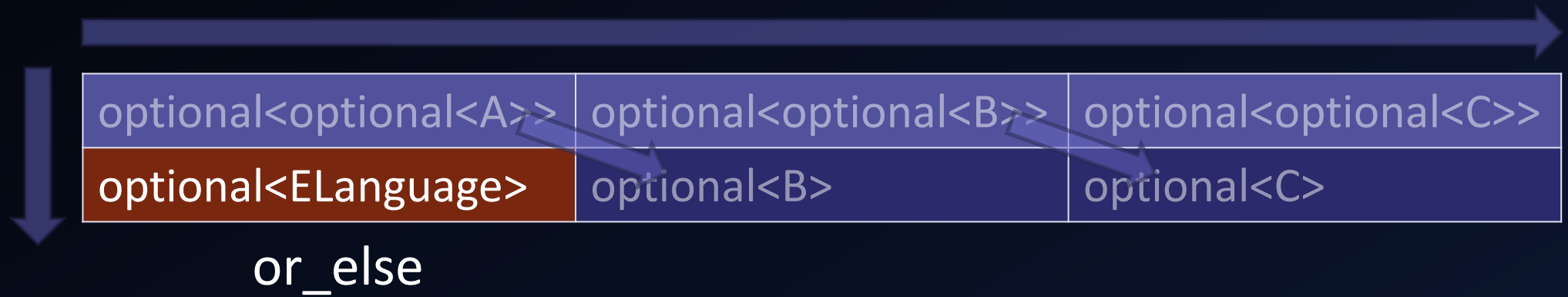
Quiz Time! Why "Monad" in Quotes?

```
return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
```



Quiz Time! Why "Monad" in Quotes?

```
return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
```



Compiler Errors

SOME HEURISTICS TO FIX THEM QUICKLY

It Compiles...Not

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

ranges::for_each(diagnostics, printDiagnostic);
```

```
x.cpp(76): error C3889: call to object of class type
'std::ranges::views::_Transform_fn': no matching call operator found
note: could be 'auto std::ranges::views::_Transform_fn::operator ()(_Rng
&&,_Fn) noexcept(<expr>) const'
note: 'auto std::ranges::views::_Transform_fn::operator ()(_Rng &&,_Fn)
noexcept(<expr>) const': expects 2 arguments - 1 provided
note: or       'auto std::ranges::views::_Transform_fn::operator ()(_Fn &&)
noexcept(<expr>) const'
x.cpp(76): note: 'auto std::ranges::views::_Transform_fn::operator ()(_Fn
&&) noexcept(<expr>) const': could not deduce template argument for '_Fn'
```

It Compiles...Not

```
auto diagnostics = projects
   | views::transform(getFilesInProject) | views::join
   | views::transform(compile)           | views::join;

ranges::for_each(diagnostics, printDiagnostic);
```

```
x.cpp(76): error C3889: call to object of class type
'std::ranges::views::_Transform_fn': no matching call operator found
note: could be 'auto std::ranges::views::_Transform_fn::operator ()(_Rng
&&,_Fn) noexcept(<expr>) const'
note: 'auto std::ranges::views::_Transform_fn::operator ()(_Rng &&,_Fn)
noexcept(<expr>) const': expects 2 arguments - 1 provided
note: or       'auto std::ranges::views::_Transform_fn::operator ()(_Fn &&)
noexcept(<expr>) const'
x.cpp(76): note: 'auto std::ranges::views::_Transform_fn::operator ()(_Fn
&&) noexcept(<expr>) const': could not deduce template argument for '_Fn'
```

Fixing Compiler Errors: Cheat Sheet

1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

```
// Split the pipeline
auto s1 = projects |
views::transform(getFilesInProject);
auto s2 = s1 | views::join;
auto s3 = s2 | views::transform(compile);
auto s4 = s3 | views::join;
```

Fixing Compiler Errors: Cheat Sheet

1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

Use wrapper lambda

Fixing Compiler Errors: Cheat Sheet

1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

```
// Make parameter types explicit
auto f1 = [](auto radius)
    { return calcArea(radius); };

auto f2 = [](double radius)
    { return calcArea(radius); };
```

Fixing Compiler Errors: Cheat Sheet

1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

```
// Make return types explicit
auto f1 = [](auto radius)
    { return calcArea(radius); };

auto f2 = [](double radius) -> double
    { return calcArea(radius); };
```

Fixing Compiler Errors: Cheat Sheet

1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

Function returns Thing
You expected vector<Thing>
(or vice versa)

Fixing Compiler Errors: Cheat Sheet

1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

Will lead to weird compiler errors.
Just Don't.

Fixing Compiler Errors: Cheat Sheet

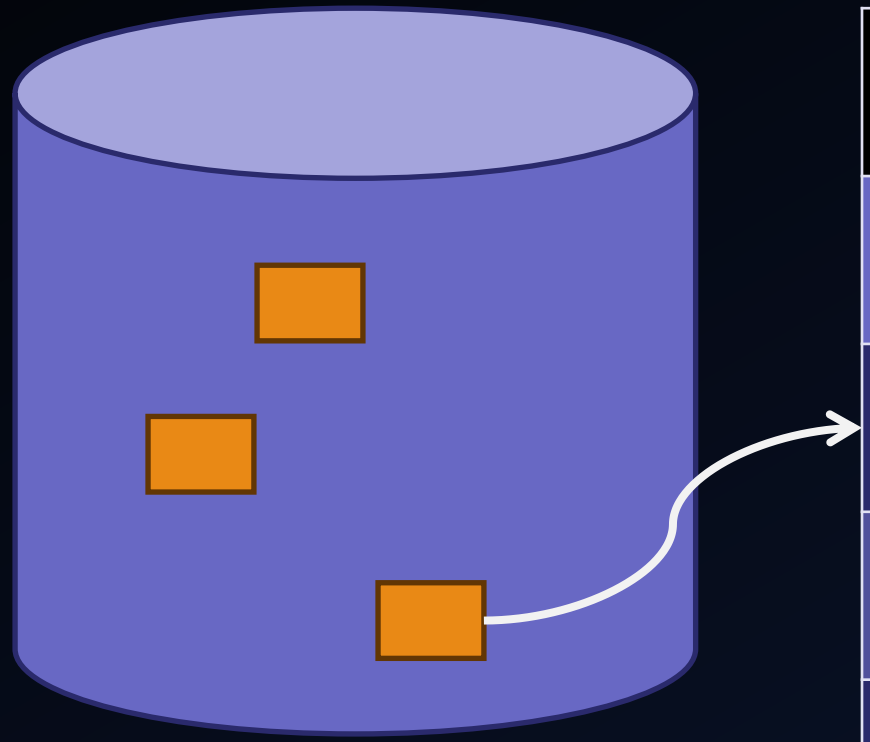
1. Which part of the pipeline causes the error?
2. Are functions overloaded?
3. Do functions accept the correct type?
4. Do functions return the correct type?
5. For ranges::views
   a) Too many / too few calls to join?
   b) const views?
6. For optional / expected
   a) Mixed up and_then with transform?

Function returns Thing
You expected optional<Thing>
(or vice versa)

Writing Your Own Monad

POINTERS INSTEAD OF OPTIONALS

Remember that "getIntCellValueNegative"?



Stock	Item	Profit
0	Cup	
2	T-Shirt	
0	Poster	
0	Statuette	-8

Negative?

Handling Failure: Classic Way...

```
bool            getElement(const CDb& db, CElementKey key, CElement& out);
bool            getTable(const CElement& element, CTable& out);
bool            getCell(const CTable& table, CLocation loc, CCell& out);
bool            getNumericCellValue(const CCell& cell, int& out);
```

...But With Pointers

```
const CElement*   getElement(const CDb& db, CElementKey key, CElement& out);
const CTable*     getTable(const CElement& element, CTable& out);
const CCell*      getCell(const CTable& table, CLocation loc, CCell& out);
optional<int>     getNumericCellValue(const CCell& cell, int& out);
```

https://godbolt.org/z/r6vYWrcfx

Handling Failure: Classic Way...

```
bool getIntCellValueNegative
    (CDb db, Key key, CLocation location, bool& out)
{
    CElement element;
    if ( ! getElement(db, key, element))          { return false; }

    CTable table;
    if ( ! getTable(element, table))              { return false; }

    CCell cell;
    if ( ! getCell(table, location, cell))        { return false; }

    int value;
    if ( ! getNumericCellValue(cell, value))      { return false; }

    result = (value < 0);
    return true;
}
```

https://godbolt.org/z/r6vYWrcfx

...But With Pointers

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   if (auto* pElement = getElement(db, key))
   {
      if (auto* pTableData = getTable(*pElement))
      {
         if (auto* pCell = getCell(*pTableData, cellLocation))
         {
            if (auto oValue = getNumericCellValue(*pCell))
            {
               return oValue.value() < 0;
            }
         }
      }
   }
   return {};
}
```

https://godbolt.org/z/r6vYWrcfx

Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
            .and_then(getTablePtr)
            .and_then([cellLocation](const auto& tableData)
                 { return getCellPtr(tableData,cellLocation); })
            .and_then(getNumericCellValue)
            .transform([](int value){ return value < 0; });
}
```

https://godbolt.org/z/hK1oxG8Tx

Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
            .and_then(getTablePtr)
            .and_then([cellLocation](const auto& tableData)
                 { return getCellPtr(tableData,cellLocation); })
            .and_then(getNumericCellValue)
            .transform([](int value){ return value < 0; });
}
```

https://godbolt.org/z/hK1oxG8Tx

Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
              .and_then(getTablePtr)
              .and_then([cellLocation](const auto& tableData)
                   { return getCellPtr(tableData,cellLocation); })
              .and_then(getNumericCellValue)
              .transform([](int value){ return value < 0; });
}
```

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Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
            .and_then(getTablePtr)
            .and_then([cellLocation](const auto& tableData)
                { return getCellPtr(tableData,cellLocation); })
            .and_then(getNumericCellValue)
            .transform([](int value){ return value < 0; });
}
```

https://godbolt.org/z/hK1oxG8Tx

Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
            .and_then(getTablePtr)
            .and_then([cellLocation](const auto& tableData)
                 { return getCellPtr(tableData,cellLocation); })
            .and_then(getNumericCellValue)
            .transform([](int value){ return value < 0; });
}
```

https://godbolt.org/z/hK1oxG8Tx

Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
            .and_then(getTablePtr)
            .and_then([cellLocation](const auto& tableData)
                 { return getCellPtr(tableData,cellLocation); })
            .and_then(getNumericCellValue)
            .transform([](int value){ return value < 0; });
}
```

Pointers

optional

Implementing A Pointer Monad

```
template<cIsPointer TPtr>
struct CPtr
{
    CPtr() = default;
    explicit CPtr(TPtr ptr);

    TPtr operator->() const;
    operator bool() const;
    bool operator!() const;

    //...

private:
    TPtr m_Ptr{};
};
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
template<cIsPointer TPtr>
struct CPtr
{
    CPtr() = default;
    explicit CPtr(TPtr ptr);

    TPtr operator->() const;
    operator bool() const;
    bool operator!() const;

    //...

private:
    TPtr m_Ptr{};
};
```

```
template<class T>
concept cIsPointer = is_pointer_v<T>;
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
template<cIsPointer TPtr>
struct CPtr
{
    CPtr() = default;
    explicit CPtr(TPtr ptr);

    TPtr operator->() const;
    operator bool() const;
    bool operator!() const;

    //...

private:
    TPtr m_Ptr{};
};
```

```
template<cIsPointer TPtr>
CPtr<TPtr>::CPtr(TPtr ptr)
    : m_Ptr(ptr)
{}
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
template<cIsPointer TPtr>
struct CPtr
{
    CPtr() = default;
    explicit CPtr(TPtr ptr);

    TPtr operator->() const;
    operator bool() const;
    bool operator!() const;

    //...

private:
    TPtr m_Ptr{};
};
```

```
template<cIsPointer TPtr>
T CPtr<TPtr>::operator->() const
{
    return m_Ptr;
}

template<cIsPointer TPtr>
CPtr<TPtr>::operator bool() const
{
    return m_Ptr;
}

template<cIsPointer TPtr>
bool CPtr<TPtr>::operator!() const
{
    return ! m_Ptr;
}
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
template<cIsPointer TPtr>
struct CPtr
{
    CPtr() = default;
    explicit CPtr(TPtr ptr);

    TPtr operator->() const;
    operator bool() const;
    bool operator!() const;

    template<class TCall>
    auto and_then(TCall&& fInvoke);
private:
    TPtr m_Ptr{};
};
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
template<cIsPointer TPtr>
template<class TCall>
auto CPtr<TPtr>::and_then(TCall&& fInvoke)
{
    using TRef = add_lvalue_reference_t<remove_pointer_t<TPtr>>;
    using TRet = invoke_result_t<TCall,TRef>;

    if constexpr (cIsPointer<TRet>)
    {
        //...return type is a pointer
    }
    else if constexpr (cbIsOptional<TRet>)
    {
        //...return type is an std::optional<something>
    }
    else
    //...
}
```

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Implementing A Pointer Monad

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{
    using TRef = add_lvalue_reference_t<remove_pointer_t<TPtr>>;
    using TRet = invoke_result_t<TCall,TRef>;

    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr));
        }
        return CPtr<TRet>{};
    }
    else if constexpr (cbIsOptional<TRet>)
    {
        //...return type is an std::optional<something>
    }
    else
    //...
}
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        return CPtr<TRet>{};
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        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
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        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
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    }
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    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return CPtr<TRet>{};
    }
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Implementing A Pointer Monad

```
    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return CPtr<TRet>{};
    }
    else if constexpr (cbIsOptional<TRet>)
    {
        if (m_Ptr)
        {
            return invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return remove_cvref_t<TRet>{};
    }
    else
    //...
}
```

```
template<class>
constexpr bool cbIsOptional                = false;
template<class T>
constexpr bool cbIsOptional<optional<T>> = true;
```

Implementing A Pointer Monad

```
    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return CPtr<TRet>{};
    }
    else if constexpr (cbIsOptional<TRet>)
    {
        if (m_Ptr)
        {
            return invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return remove_cvref_t<TRet>{};
    }
    else
    //...
}
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return CPtr<TRet>{};
    }
    else if constexpr (cbIsOptional<TRet>)
    {
        if (m_Ptr)
        {
            return invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return remove_cvref_t<TRet>{};
    }
    else
    //...
}
```

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Implementing A Pointer Monad

```
    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return CPtr<TRet>{};
    }
    else if constexpr (cbIsOptional<TRet>)
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        {
            return invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return remove_cvref_t<TRet>{};
    }
    else
    //...
}
```

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Implementing A Pointer Monad

```
    if constexpr (cIsPointer<TRet>)
    {
        if (m_Ptr)
        {
            return CPtr<TRet>(invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return CPtr<TRet>{};
    }
    else if constexpr (cbIsOptional<TRet>)
    {
        if (m_Ptr)
        {
            return invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return remove_cvref_t<TRet>{};
    }
    else
    //...
}
```

https://godbolt.org/z/hK1oxG8Tx

Implementing A Pointer Monad

```
    else if constexpr (cbIsOptional<TRet>)
    {
        if (m_Ptr)
        {
            return invoke(forward<TCall>(fInvoke),*m_Ptr);
        }
        return remove_cvref_t<TRet>{};
    }
    // else if constexpr (function already returns CPtr) ...
    // else if constexpr (function returns std::expected) ...
    else
    {
        static_assert(false, "returns neither pointer nor optional");
    }
}
```

https://godbolt.org/z/hK1oxG8Tx

Using the Pointer Monad

```
std::optional<bool> getIntCellValueNegative
      (const CDb& db, const Key& key, const CLocation& cellLocation)
{
   return CPtr(getElementPtr(db,key))
            .and_then(getTablePtr)
            .and_then([cellLocation](const auto& tableData)
                 { return getCellPtr(tableData,cellLocation); })
            .and_then(getNumericCellValue)
            .transform([](int value){ return value < 0; });
}
```

Pointers

optional

https://godbolt.org/z/hK1oxG8Tx

Pointer Monad – Summary

Writing monads
is not magic!

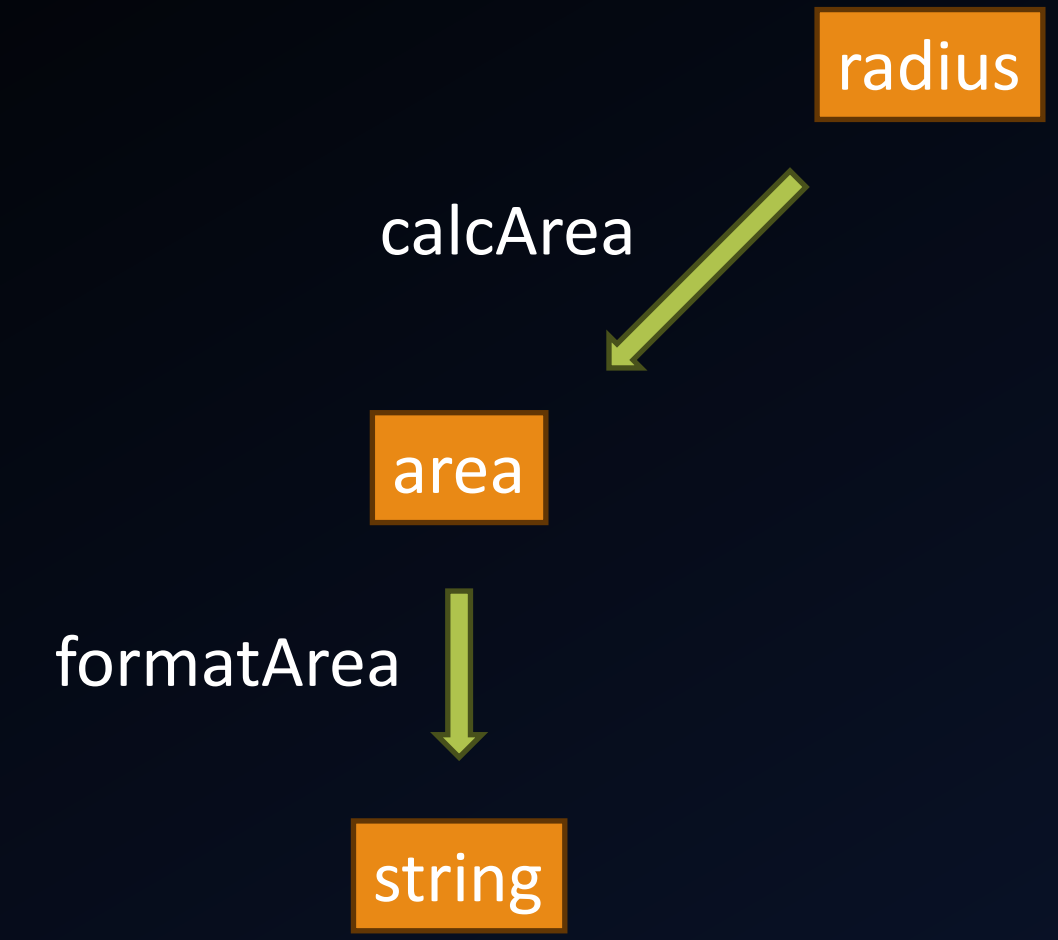
Brush up your metaprogramming

- Start specific, then generalize
- Consider effects of value categories (const, &,...)
- Use concepts and static_assert to prevent misuse at compile time

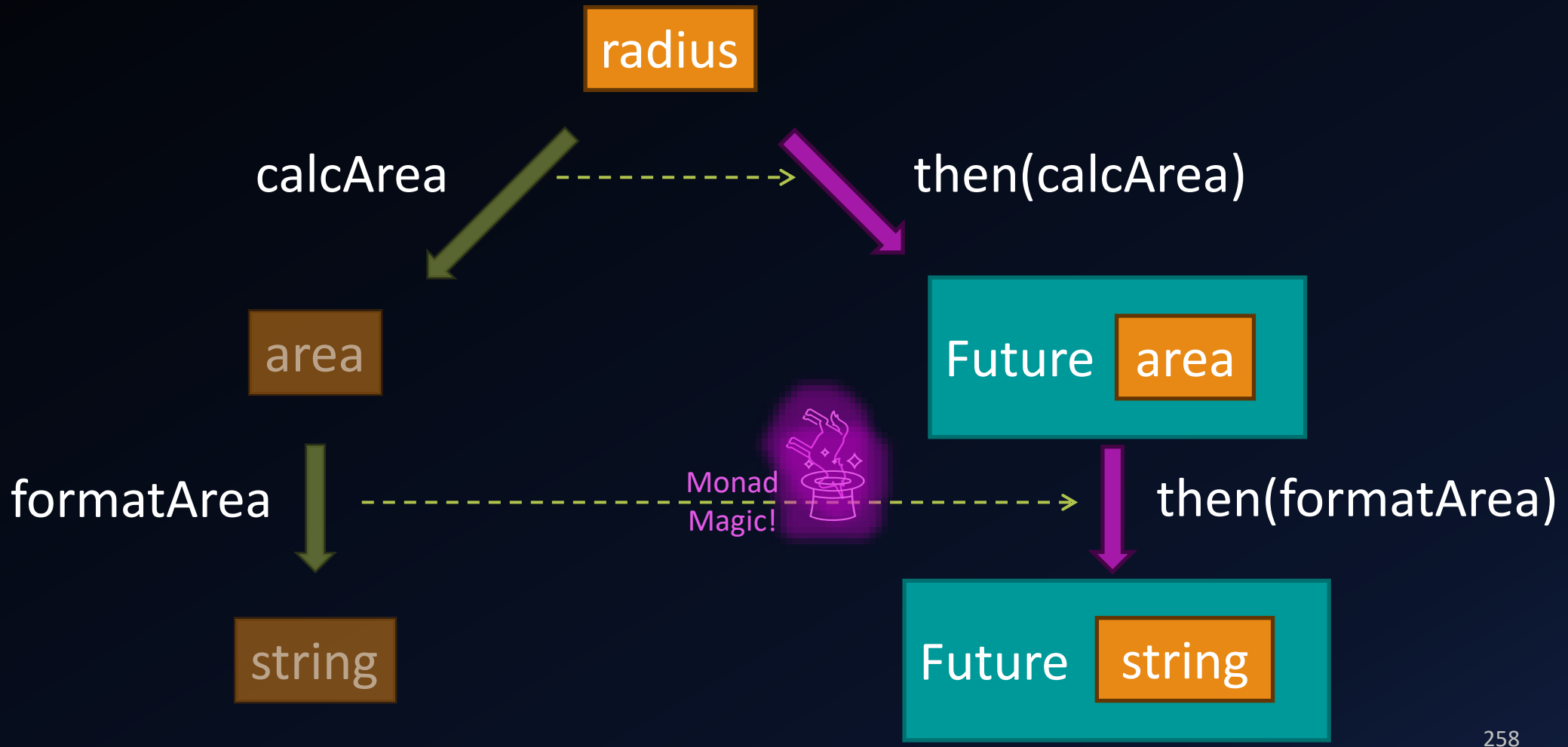
Combining Monads

CONTINUATION & WRITER

A Pipeline of Slow, Blocking Tasks



Continuation Monad



Using QtConcurrent With Continuation

```
double calcArea(double radius);
string formatArea(double area);

auto future = QtConcurrent::run(calcArea, initialValue)
                    .then(formatArea);

//...
auto result = future.result();  // blocks until result is ready
print("Result: {:}", result);
```

https://godbolt.org/z/33aaco98c

Using QtConcurrent With Continuation

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double calcArea(double radius);
string formatArea(double area);

auto future = QtConcurrent::run(calcArea, initialValue)
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auto result = future.result();  // blocks until result is ready
print("Result: {:}", result);
```

How to trace such a pipeline
Lock-free and **preserving order**

https://godbolt.org/z/33aaco98c

Using a Writer Monad

```
double calcArea(double radius);
string formatArea(double area);

auto result = CWriter(inputValue)
    .and_then(calcArea, CTraceEntry{"Some trace"})
    .and_then(formatArea, CTraceEntry{"Other trace"});

print("Result: {:} ", result.m_Value);
for(const auto& item : result.m_Trace)
{
    print("{:}",CTraceEntry::toString);
}
```

https://godbolt.org/z/r437Ea7bj

Using a Writer Monad

```
double calcArea(double radius);
string formatArea(double area);

auto result = CWriter(inputValue)
    .and_then(calcArea, CTraceEntry{"Some trace"})
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for(const auto& item : result.m_Trace)
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    print("{:}",CTraceEntry::toString);
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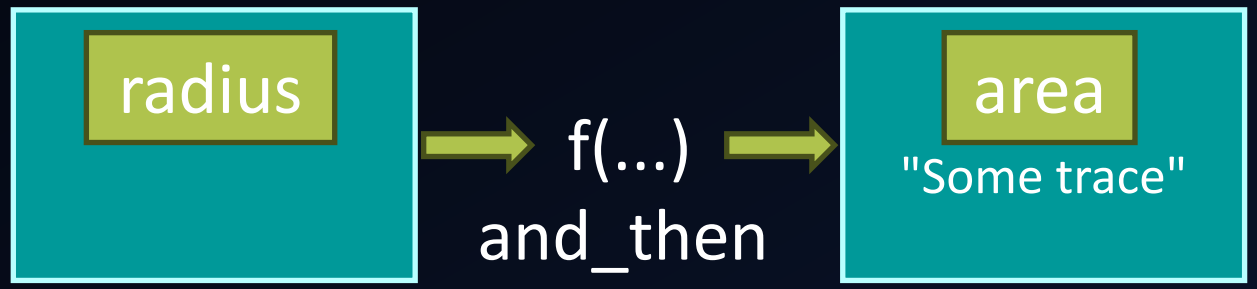
```



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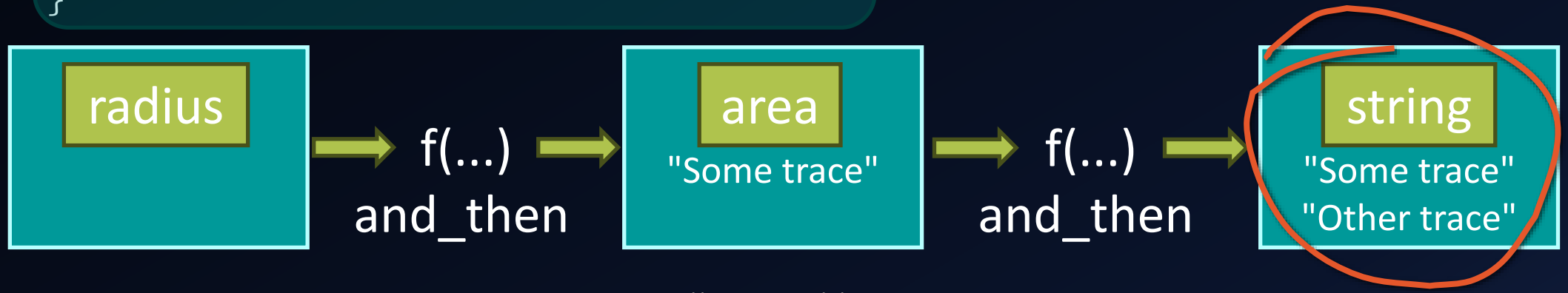


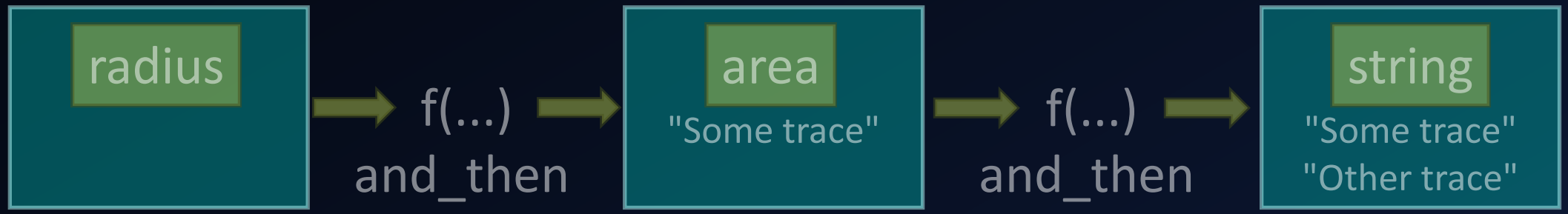
https://godbolt.org/z/r437Ea7bj

Functions Returning Trace: Total Flexibility

```
CWriterValueAndTrace<double> calcArea(double radius);
CWriterValueAndTrace<string> formatArea(double area);

auto result = CWriter(inputValue)
    .and_then(calcArea)
    .and_then(formatArea);

print("Result: {:} ", result.m_Value);
for(const auto& item : result.m_Trace)
{
    print("{:}",CTraceEntry::toString);
}
```



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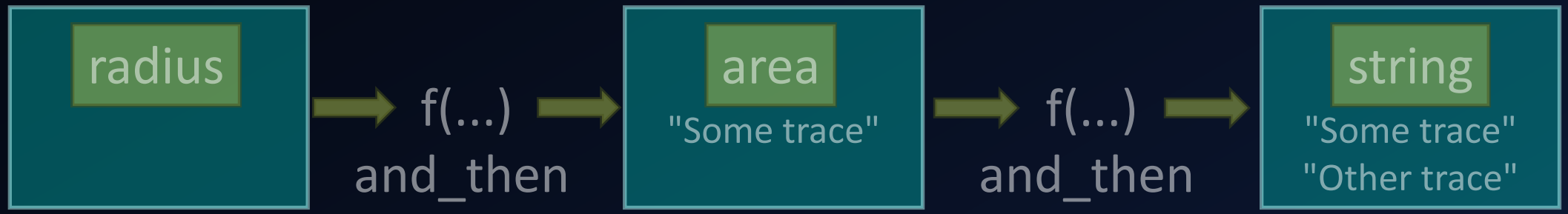
for(const auto& item : result.m_Trace)
{
    print("{:}",CTraceEntry::toString);
}
```



https://godbolt.org/z/r437Ea7bj

Combining Continuation and Writer

```
CWriterValueAndTrace<double> calcArea(double radius);
CWriterValueAndTrace<string> formatArea(double area);

auto future = QtConcurrent::run(makeWriter, inputValue)
                    .then(addWriterApi(calcArea))
                    .then(addWriterApi(formatArea));

CWriter<string> result = future.result();  // blocks
print("Result: {:}", result.m_Value);

for(const auto& item : result.m_Trace)
{
    print("{:}",CTraceEntry::toString);
}
```

https://godbolt.org/z/hbEaWjxj7

Combining Continuation and Writer

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CWriterValueAndTrace<double> calcArea(double radius);
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print("Result: {:}", result.m_Value);

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print("Result: {:}", result.m_Value);

for(const auto& item : result.m_Trace)
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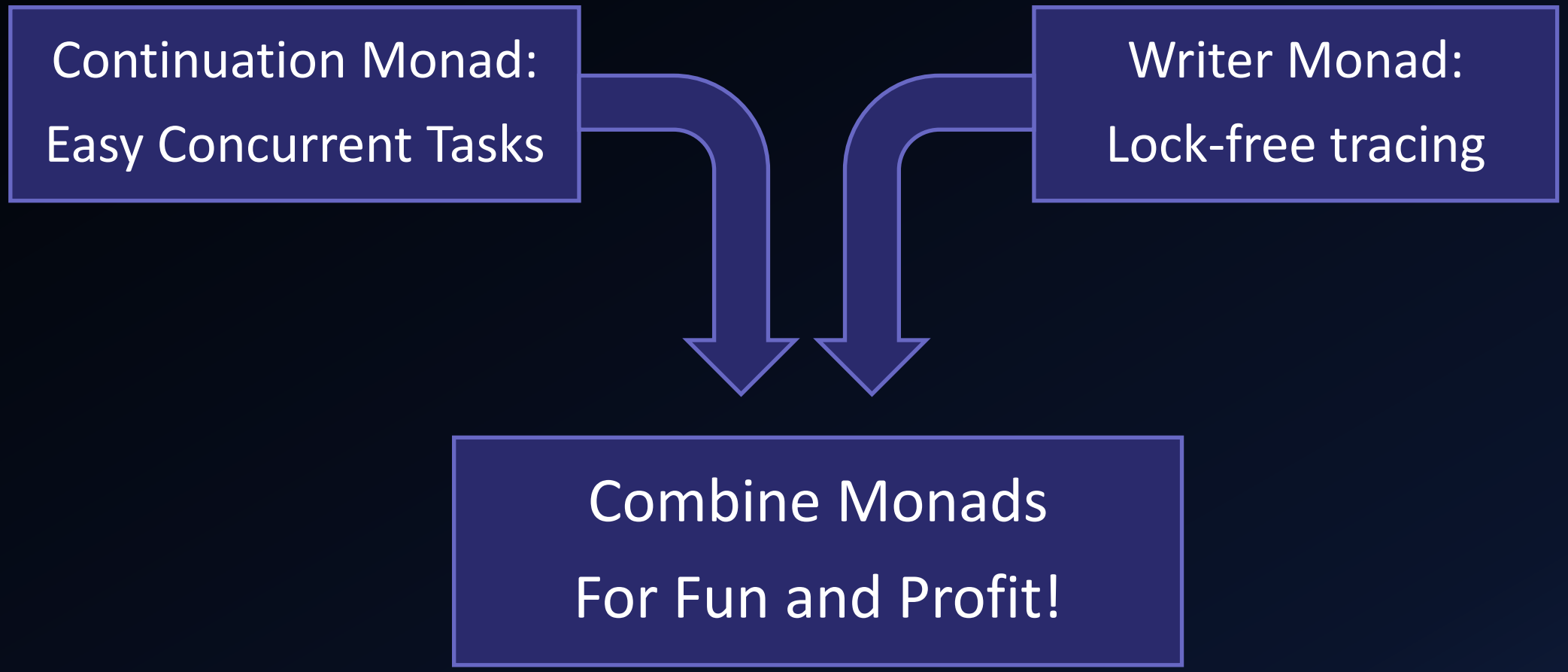
    print("{:}",CTraceEntry::toString);
}
```

https://godbolt.org/z/hbEaWjxj7

Combining Monads: Summary



What Now?

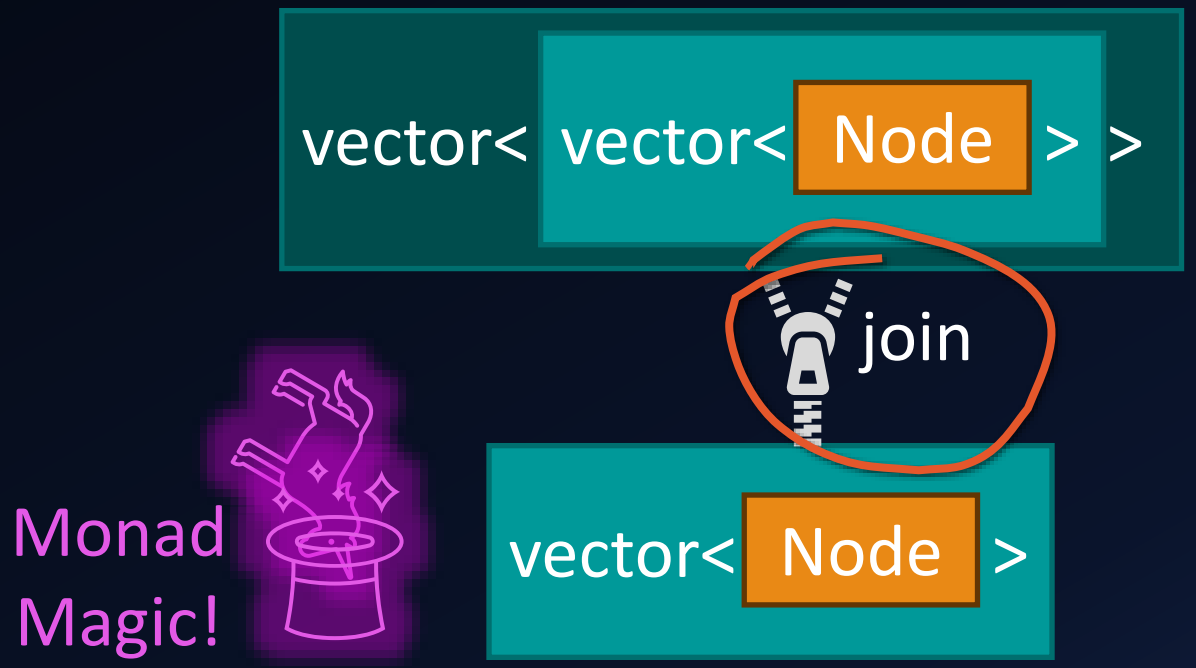
MONADIC OPERATIONS AND YOU

Takeaways

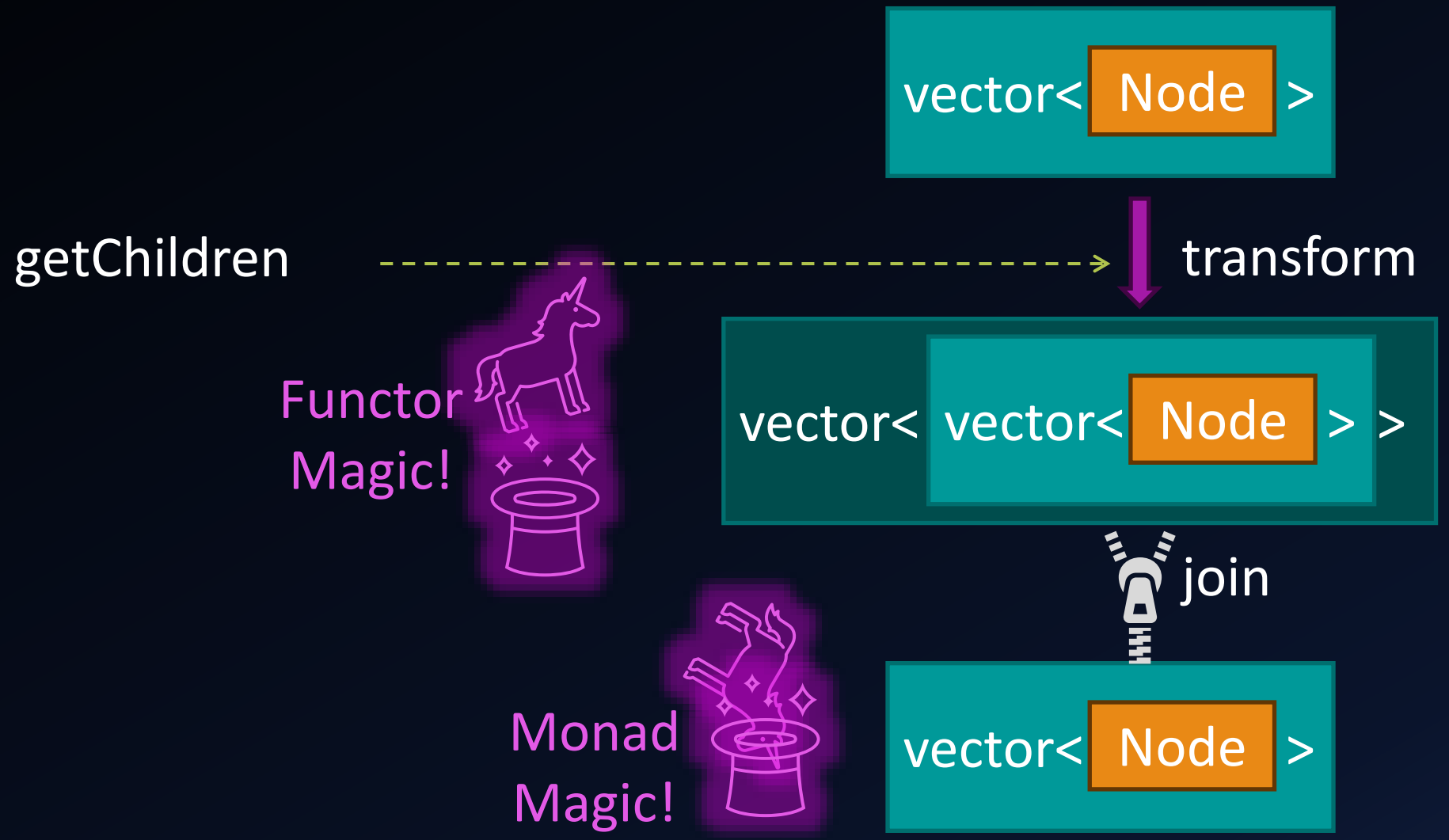
Functors and Monads are useful concepts to know about

Functor Magic!

Monad Magic!



Functors and Monads

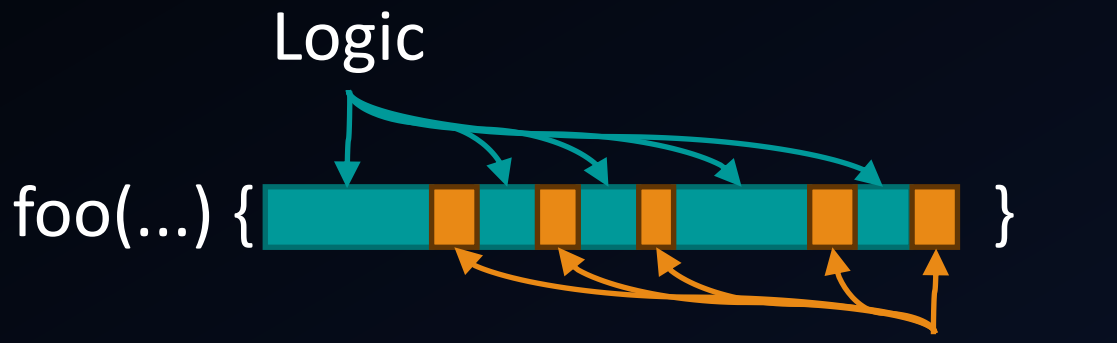


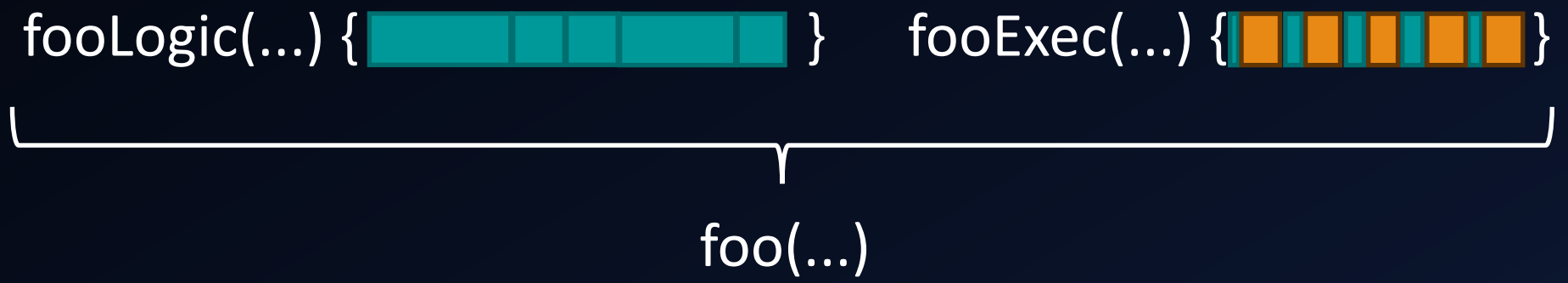
Takeaways

Functors and Monads are useful concepts to know about

Pure functions are good for your code

Pure Functions are Good For Your Code





Takeaways

Functors and Monads are useful concepts to know about

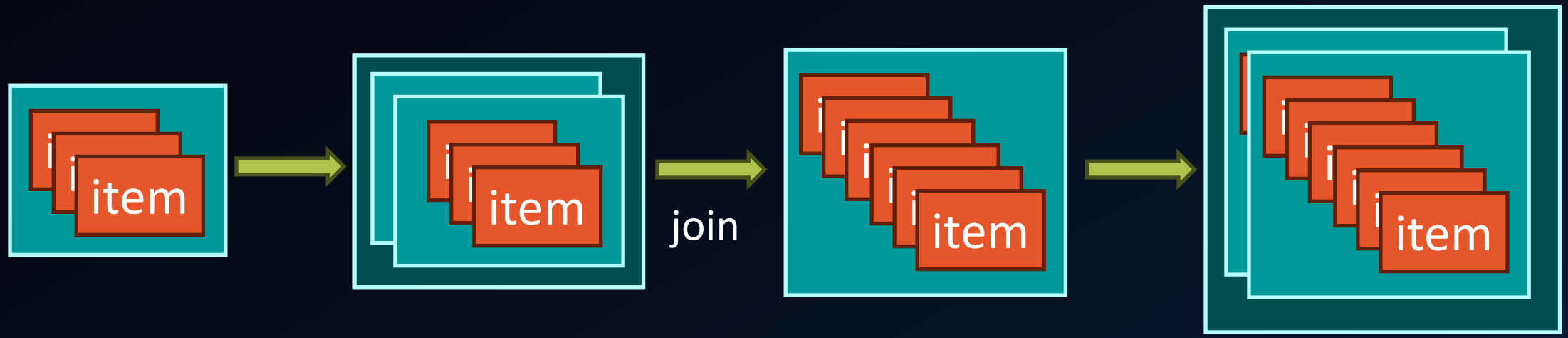
Pure functions are good for your code

Monadic Operations in C++23 are immediately useful in common use cases

Ranges / Views Monad

```
auto diagnostics = projects
    | views::transform(getFilesInProject) | views::join
    | views::transform(compile)           | views::join;

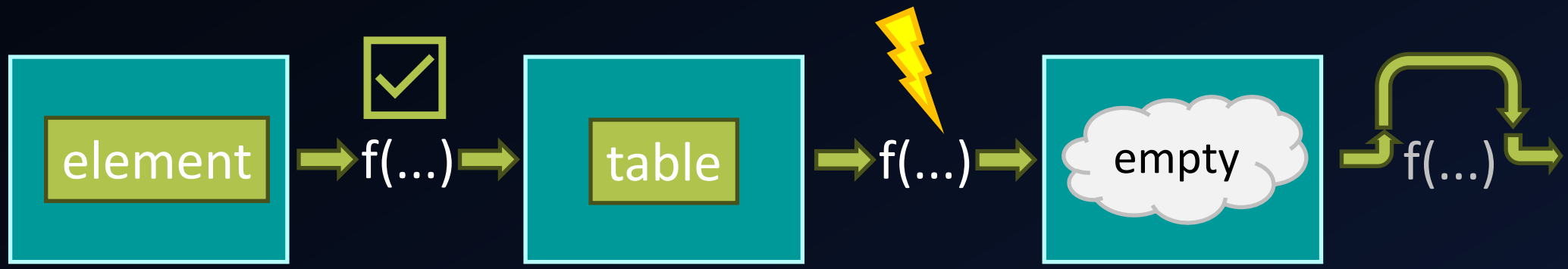
ranges::for_each(diagnostics, printDiagnostic);
```



https://godbolt.org/z/W5dqnavYc

Optional (Maybe) Monad

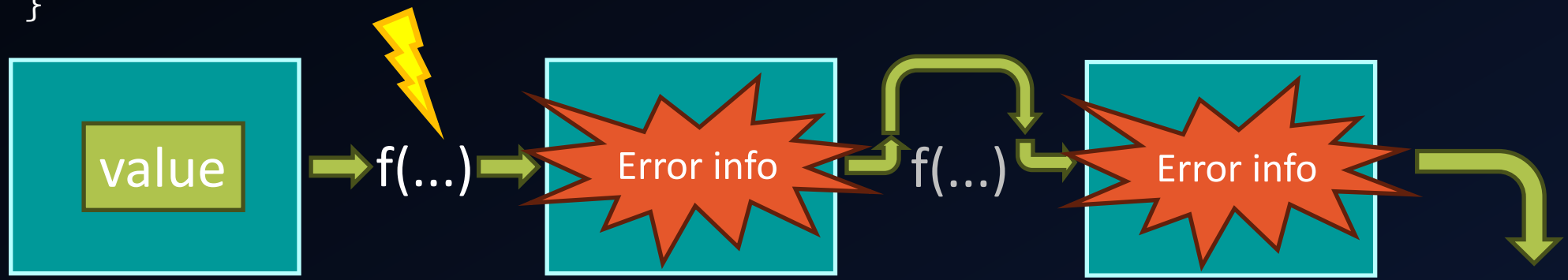
```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
       .and_then(getTable)
       .and_then([location](CTable table)
                 { return getCell(table, location); })
       .and_then(getNumericCellValue)
       .transform(isNegative);
}
```



https://godbolt.org/z/rfW6EM68b

Expected Monad

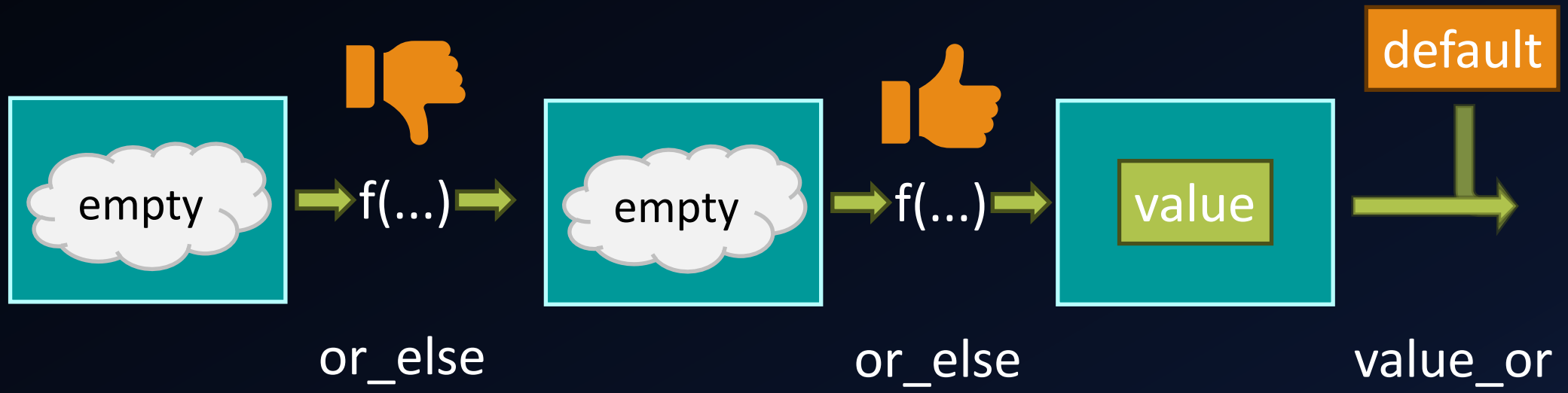
```
optional<bool> isIntCellValueNegative(CDb db, Key key, CLocation location)
{
    return getElement(db, key)
        .and_then(getTable)
        .and_then([location](CTable table)
                  { return getCell(table, location); })
        .and_then(getNumericCellValue)
        .transform(isNegative)
        .or_else(log<bool>);
}
```



https://godbolt.org/z/sKGb6qPo9

Default “Monad”

```
ELanguage getStartupLanguage()
{
    return getLanguageFromCommandLine()
            .or_else(getLanguageFromRegistry)
            .or_else(getLanguageFromEnvironment)
            .value_or(ELanguage::English);
}
```

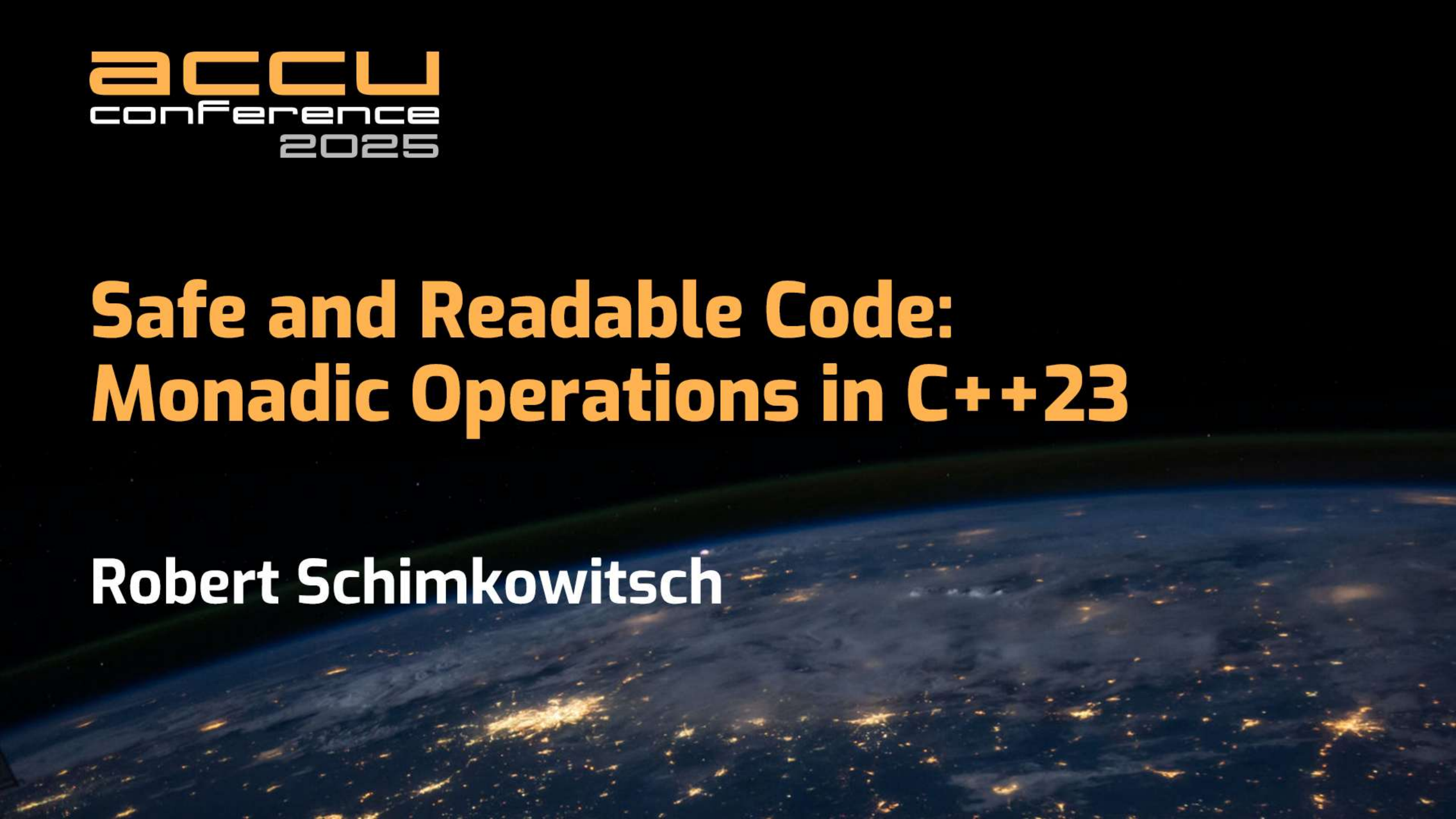


https://godbolt.org/z/zz5coz13T

accu conference 2025

Safe and Readable Code: Monadic Operations in C++23

Robert Schimkowitsch



References, Code, Slides

Thanks go to:

- My family
- Ivan Čukić
- C++ User Group Vienna
- MUC++
- #include community

https://github.com/Asperamanca/monadic_operations_cpp23