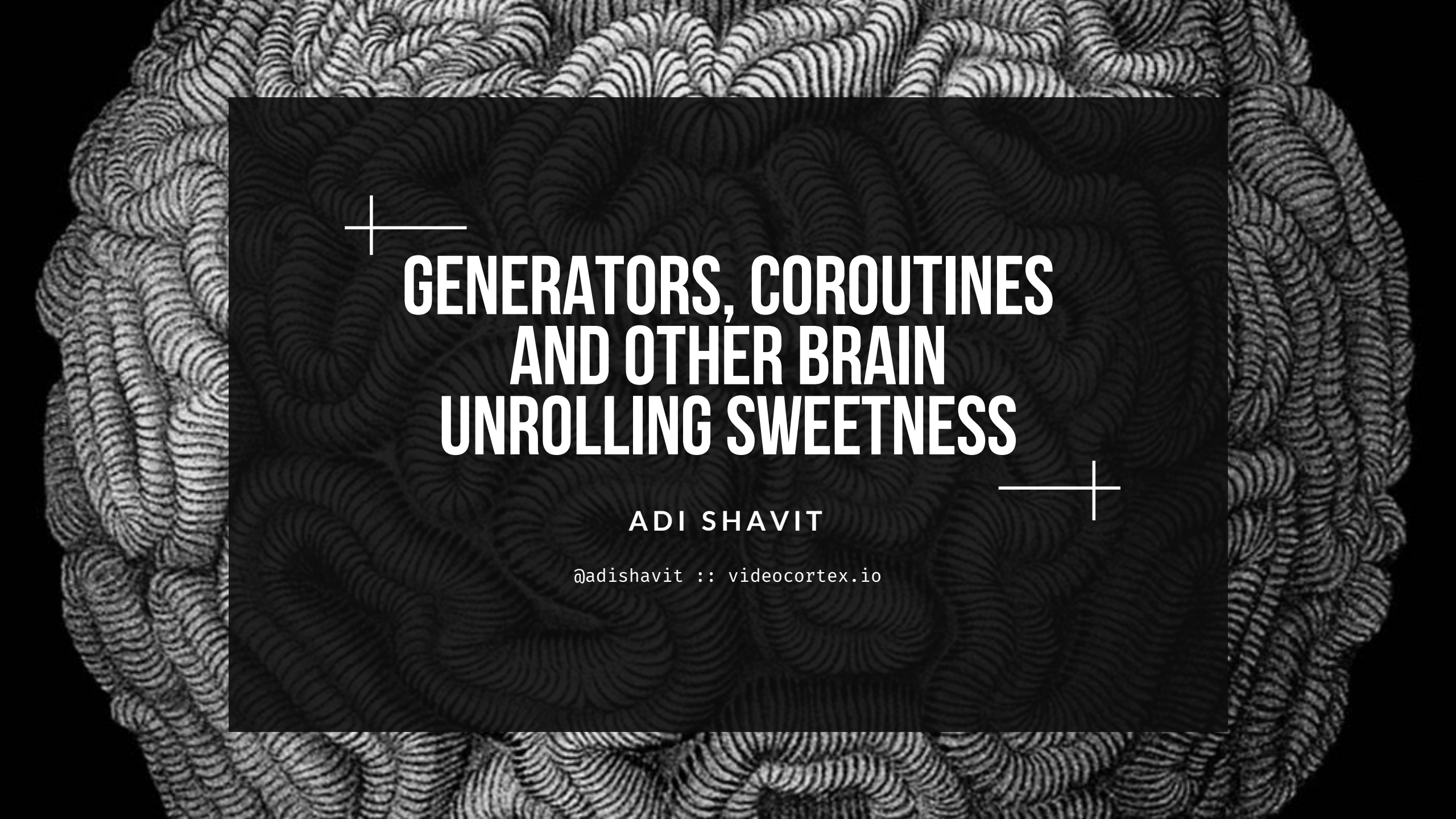


Generators, Coroutines and other brain unrolling sweetness

ADI SHAVIT

@adishavit :: videocortex.io

FUNCTIONS & SUB-ROUTINES

- Let's iterate!
- One function:
  1. Iterates
  2. Operates

```
void vectorate(std::vector<int> const& v)
{
    for (auto e: v)                 // 1. iterate
        std::cout << e << '\n';     // 2. do something: print e
}
```

- What if we need another operation?
  - Sum?
  - Both?

1947

DID YOU KNOW?

The concept of a function, or **sub-routine** goes back to one of the first computers, the ENIAC, in the late 1940s and the term **sub-routine** is from the early 1950s.

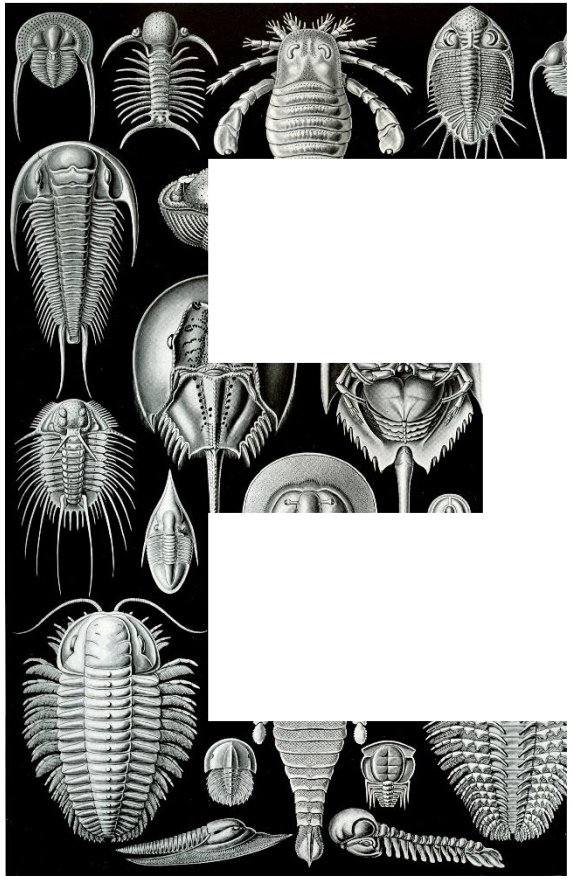
FUNCTIONS & SUB-ROUTINES

- Let's draw!
- One function:
    1. Iterates
    2. Operates

Assumes `putpixel()`

1. Available;
2. Correct signature;
3. Does the right thing;
4. Returns control to caller!

```
void drawline(int x0, int y0, int x1, int y1) // Partial Bresenham
{
    int dy=y1-y0;
    int x=x0;
    int y=y0;
    int p=2*dy-dx;
    while(x<x1)                    // 1. iterate
    {
       putpixel(x,y,7);            // 2. do something: call putpixel()
       if(p>=0)
       {
           y=y+1;
           p=p+2*dy-2*dx;
       }
       else
       {
           p=p+2*dy;
       }
       x=x+1;
    }
}
```

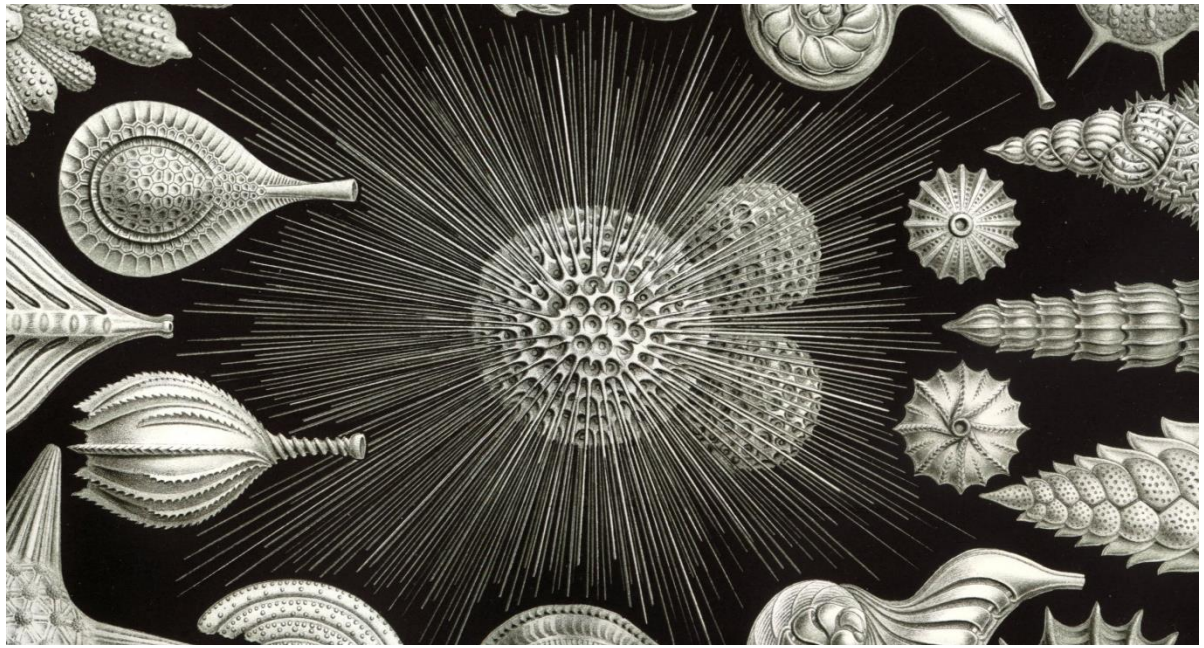


SUBROUTINES ARE EAGER AND CLOSED

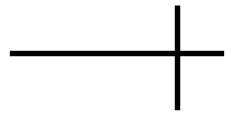
EAGER PROCESSING

"Closed" in the sense that they only return after they have iterated over the whole sequence. They eagerly process a whole sequence.

CALLBACKS

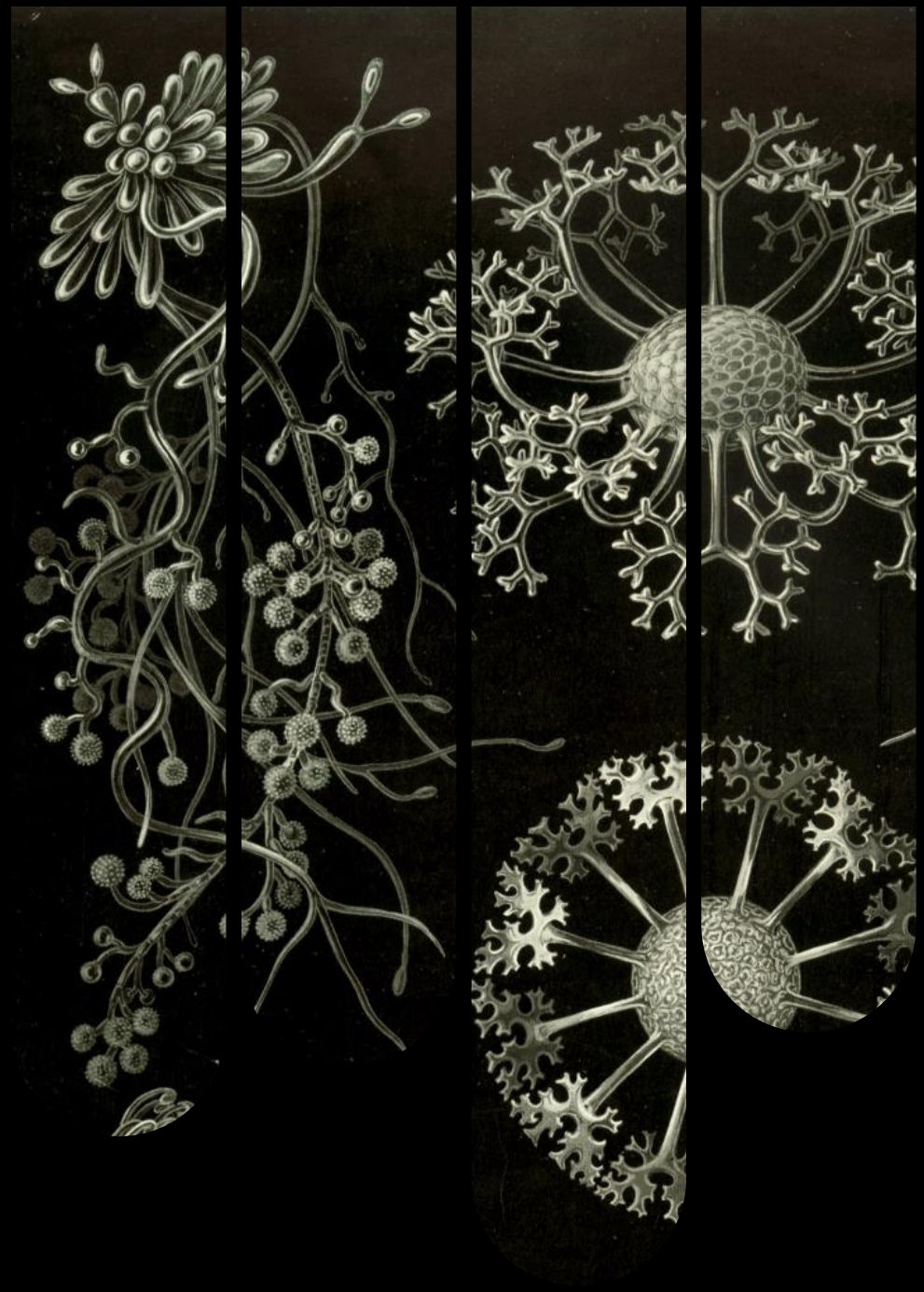


- INVERSION-OF-CONTROL
- CALLBACK HELL
- STILL EAGER



EXTERNAL CALLABLES

- Function pointers
- Lambdas
- Callable template parameters or Concepts



CAN WE BREAK THEM OPEN?

If only there was a way to “flip” these iterating functions “inside-out” and iterate over a sequence without pre-committing to a specific operation.

ITERATORS

- Iterator Objects and Iterator Adaptors
  - “Stand-alone” types;
  - Often indirectly or implicitly coupled to a sequence

- Examples from the C++ standard:
  - `std::istream_iterator`
  - `std::reverse_iterator`
  - `std::recursive_directory_iterator`

1998

DID YOU KNOW?

The concept of Iterators has been with C++ since the STL was designed by Alex Stepanov and together with the rest of the STL became part of C++98.

USER DEFINED ITERATORS

OpenCV's `cv::LineIterator`

- Typical Iterator API
- No explicit sequence
- *Lazily generate* elements
- Incremental access to pixels along a line

```
class LineIterator
{
public:
    // creates iterator for the line connecting pt1 and pt2 in img
    // the 8-connected or 4-connected line will be clipped on the image boundaries
    LineIterator( const Mat& img, Point pt1, Point pt2, int connectivity = 8);
    uchar* operator *();           // returns pointer to the current pixel
    LineIterator& operator ++();   // prefix increment operator (++it). shifts
iterator to the next pixel

    // public (!!!) members [ <groan 😩> ]
    uchar* ptr;
    const uchar* ptr0;
    int step, elemSize;
    int err, count;
    int minusDelta, plusDelta;
    int minusStep, plusStep;
};
```

USER DEFINED ITERATORS

Example Usage

```
cv::LineIterator it(img, pt1, pt2, 8);
std::vector<cv::Vec3b> buf(it.count);
for(int i = 0; i < it.count; ++i, ++it) // copy pixel values along the line into buf
    buf[i] = *(const cv::Vec3b*)*it;
```

```
class LineIterator
{
public:
    // creates iterator for the line connecting pt1 and pt2 in img
    // the 8-connected or 4-connected line will be clipped on the image boundaries
    LineIterator( const Mat& img, Point pt1, Point pt2, int connectivity = 8);
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    // public (!!!) members [ <groan 😩> ]
    uchar* ptr;
    const uchar* ptr0;
    int step, elemSize;
    int err, count;
    int minusDelta, plusDelta;
    int minusStep, plusStep;
};
```
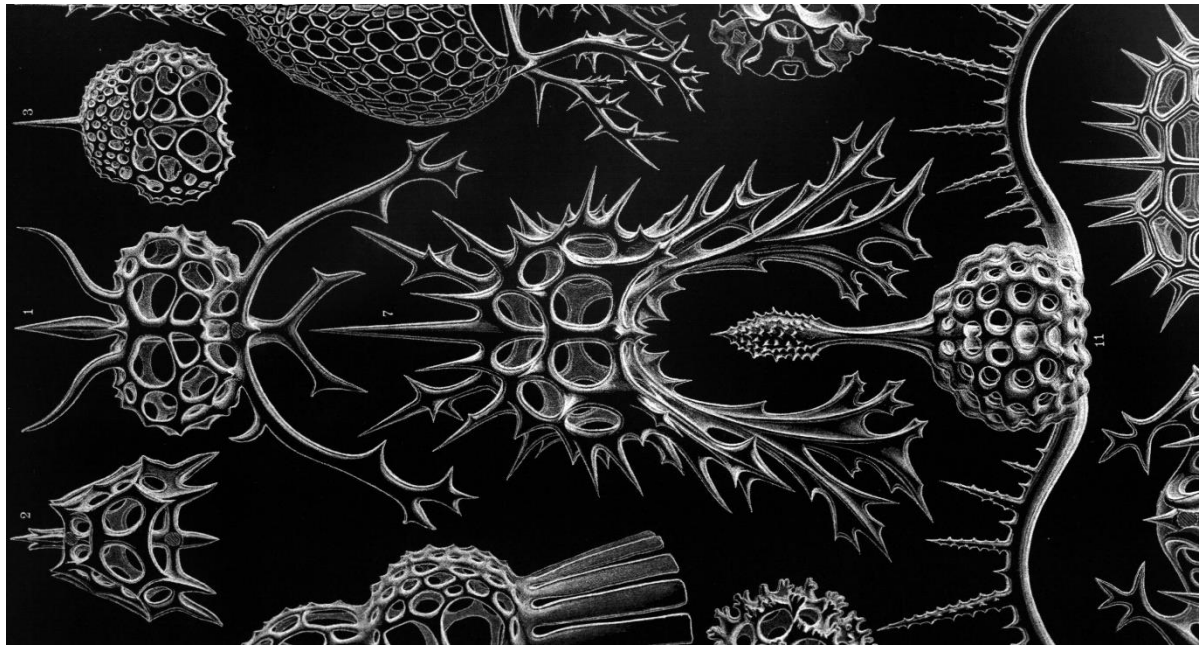

OBJECTS THAT LAZILY GENERATE VALUES ARE CALLED

GENERATORS

ABSTRACTION

IMPERFECT



- AWKWARD COUPLING
- DISTRIBUTED LOGIC

NOT TO MENTION

- Horrible public members
- Dereferencing operator * requires casting

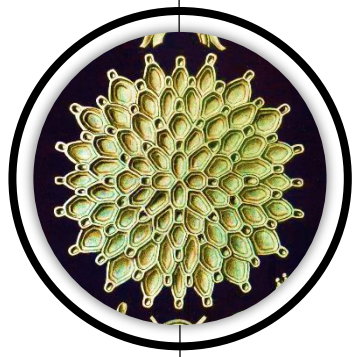
AWKWARD COUPLING

When do we stop incrementing?

- `cv::LineIterator`: at most `it.count` times
- `std::istream_iterator`: when == `std::istream_iterator()`
- `std::reverse_iterator`: when == sequence `rend()`
- `std::recursive_directory_iterator` when == `std::end(it)`

PITFALL! USER SIDE RUNTIME COUPLING OF BEGIN AND END

RANGES



- Abstraction layer on top of iterators
- The answer to **The Awkward Coupling**
- C++20 Ranges encapsulate:
  - A begin and end iterator-pair;
  - An iterator + size;
  - An iterator and stopping condition
- A single object that makes STL iterators and algorithms more powerful by making them composable.
- Create pipelines to transform values

2020+

DID YOU KNOW?

Ranges are coming to C++20 and are an amazing new addition to the standard library! Three pillars: Views, Actions, and Algorithms.

DISTRIBUTED LOGIC

Cousin of **Callback Hell**:

- Distributed logic:
  - Logic split between ctor and methods like operator++
- Centralized-state:
  - Intermediate computation variables stored as (mutable) members.

```
class LineIterator
{
public:
    // creates iterator for the line connecting pt1 and pt2 in img
    // the 8-connected or 4-connected line will be clipped on the image boundaries
    LineIterator( const Mat& img, Point pt1, Point pt2, int connectivity = 8);
    uchar* operator *();           // returns pointer to the current pixel
    LineIterator& operator ++();   // prefix increment operator (++it). shifts
iterator to the next pixel



    uchar* ptr;
    const uchar* ptr0;
    int step, elemSize;
    int err, count;
    int minusDelta, plusDelta;
    int minusStep, plusStep;
};
```

```
//...
inline uchar* LineIterator::operator *()         // trivial
{   return ptr; }

inline LineIterator& LineIterator::operator ++() // loop iteration logic
{
    int mask = err < 0 ? -1 : 0;
    err += minusDelta + (plusDelta & mask);
    ptr += minusStep + (plusStep & mask);
    return *this;
}
//...
```

LOGIC PUZZLE

```
void processLine(const Mat& img, Point pt1, Point pt2,...)
{
    // local variables (cv::LineIterator member variables)
    uchar* ptr;
    const uchar* ptr0;
    int step, elemSize;
    int err, count;
    int minusDelta, plusDelta;
    int minusStep, plusStep;

    // initialize local variable (cv::LineIterator::LineIterator() ctor)
    // ...

    // Now draw the line
    for(int i = 0; i < count; ++i) // the explicit loop
    {
        // calculate the next element (LineIterator::operator++())
        int mask = err < 0 ? -1 : 0;
        err += minusDelta + (plusDelta & mask);
        ptr += minusStep + (plusStep & mask);

        doSomething(ptr); // <<!!! ptr is the "current" element/pixel
    }
```

CENTRALIZED LOGIC
EAGER & CLOSED

```
class LineIterator
{
public:
    // creates iterator for the line connecting pt1 and pt2 in img
    // the 8-connected or 4-connected line will be clipped on the image boundaries
    LineIterator( const Mat& img, Point pt1, Point pt2, int connectivity = 8);
    uchar* operator *();            // returns pointer to the current pixel
    LineIterator& operator ++();    // prefix increment operator (++it). shifts
iterator to the next pixel


    uchar* ptr;
    const uchar* ptr0;
    int step, elemSize;
    int err, count;
    int minusDelta, plusDelta;
    int minusStep, plusStep;
};
```

DISTRIBUTED LOGIC
LAZY & OPEN

```
//...
inline uchar* LineIterator::operator *()         // trivial
{   return ptr; }

inline LineIterator& LineIterator::operator ++() // loop iteration logic
{
    int mask = err < 0 ? -1 : 0;
    err += minusDelta + (plusDelta & mask);
    ptr += minusStep + (plusStep & mask);
    return *this;
}
//...
```

CAN WE HAVE NICE THINGS?

If only there was a way to write easy to reason about, serial algorithms with local scoped variables while still abstracting way the iteration…

COROUTINES

"Coroutines make it trivial to define your own ranges."
— Eric Niebler

A Coroutine is **a function** that:

1. Can suspend execution;
2. Resume later;
3. Preserve local state;
4. Allows re-entry more than once;
5. Non-pre-emptive → Cooperative

JUST LIKE WHAT WE WANT!

1958

DID YOU KNOW?

The term A coroutine was coined by Melvin Conway in 1958. Boost has had several coroutine libraries at least since 2009 and some C coroutine libraries were well known since before 2000.

COROUTINES

"Coroutines make it trivial to define your own ranges."
— Eric Niebler

A Coroutine is **a function** that:

1. Can suspend execution;
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4. Allows re-entry more than once;
5. Non-pre-emptive → Cooperative

```
void processLine(const Mat& img, Point pt1, Point pt2,...)
{
    // local variables (cv::LineIterator member variables)
    uchar* ptr;
    const uchar* ptr0;
    int step, elemSize;
    int err, count;
    int minusDelta, plusDelta;
    int minusStep, plusStep;

    // initialize local variable (cv::LineIterator::LineIterator() ctor)
    // ...

    // Now draw the line
    for(int i = 0; i < count; ++i) // the explicit loop
    {
        // calculate the next element (LineIterator::operator++())
        int mask = err < 0 ? -1 : 0;
        err += minusDelta + (plusDelta & mask);
        ptr += minusStep + (plusStep & mask);

?       doSomething(ptr); // <<!!! ptr is the "current" element/pixel
    }
```

C++20 COROUTINES

- The answer to **Distributed Logic**
- A **function** is a coroutine if any of the following:
  - Uses `co_await` to suspend execution until resumed;
  - Uses `co_yield` to suspend + returning a value;
  - Uses `co_return` to complete + return a value.
- Return type must satisfy some requirements.

CANNOT TELL COROUTINE FROM FUNCTION BY SIGNATURE

2020+

DID YOU KNOW?

Coroutines suspend execution by returning to the caller and the data required to resume execution is stored separately from the caller-stack. To make this even more confusing they are called *Stackless* do distinguish them from *Stackful* coroutines which use CPU/OS fibers)).

THE SIMPLEST CODE

```
auto zoro() { return 42; }
```

- What does `zoro()` return?
- The return type is… ?
- Is it a coroutine?

THE SIMPLEST CODE

```
auto zoro() { return 42; }
```

- What does **`zoro()`** return? **`42`**
- The return type is… **`int`**
- Is it a coroutine? No

```
auto coro() { co_yield 42; }
```

- What does **`coro()`** return?
- The return type is… ?
- Is it a coroutine?

THE SIMPLEST CODE

```
auto zoro() { return 42; }
```

- What does **`zoro()`** return? **`42`**
- The return type is… **`int`**
- Is it a coroutine? No

```
auto coro() { co_yield 42; }
```

- What does **`coro()`** return? Not **`42`**
- The return type is… ? Not **`int`**
- Is it a coroutine? Yes

THE SIMPLEST CODE

```
auto gen = coro();      // the (suspended) generator
auto it = gen.begin();  // the iterator: resumes the coroutine, executing it until it
encounters co_yield
cout << *it;            // dereference to get the actual value.

// or alternatively
cout << *coro().begin();
```

OR

```
for (auto v: coro())
    cout << v;
```

INFINITE RANGES

```
auto iota(unsigned int n = 0)
{
  while(true)
    co_yield n++;
}

// usage:
std::copy_n(iota(42).begin(), 9, std::ostream_iterator<int>(std::cout, ","));
// prints: 42,43,44,45,46,47,48,49,50
```

DECEPTION

- NO AUTO RETURN TYPE
- NO STD CORO LIBRARY!

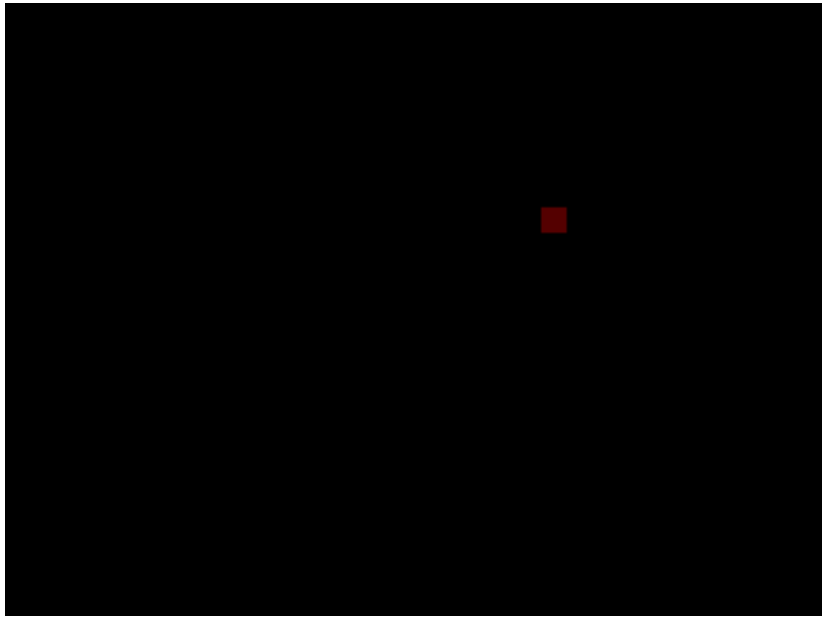
MSVC EXTENSIONS

- Non-conforming MSVC infers `std::experimental::generator<T>` for `auto`
- No such thing as `std::experimental::generator<T>`
- Until then, use e.g. Lewis Baker's `cppcoro`

```
auto spiral()
{
    int x = 0, y = 0;
    while (true)
    {
        co_yield Point{ x, y }; // yield the current position on the spiral
        if (abs(x) <= abs(y) && (x != y || x >= 0))
            x += ((y >= 0) ? 1 : -1);
        else
            y += ((x >= 0) ? -1 : 1);
    }
}
```

SPIN CYCLE

```
auto hueCycleGen(int step = 1)
{
    Mat3b rgb(1,1), hsv(1,1);
    hsv(0,0) = { 0, 255, 255 }; // { Hue=0, Full Saturation, Full Intensity }
    while (true)
    {
        cvtColor(hsv, rgb, COLOR_HSV2RGB_FULL);
        co_yield rgb(0,0); // yield the current RGB corresponding to the current HSV.
        (hsv(0,0)[0] += step) %= 255; // cycle the H channel
    }
}
```

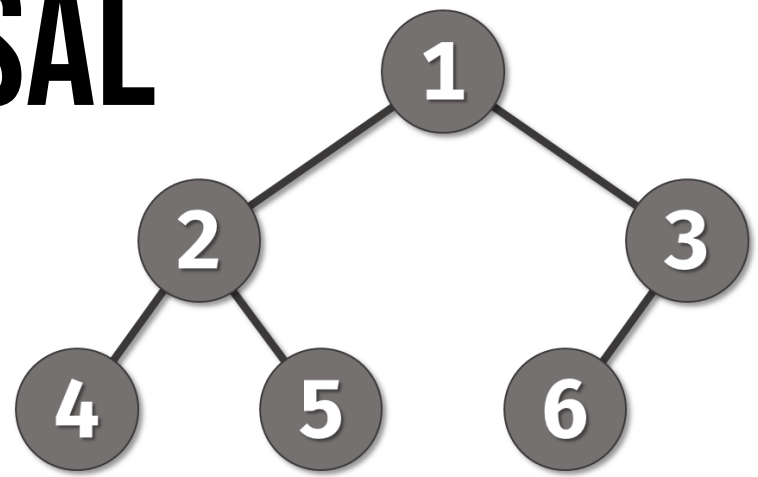


```
template <typename T, typename U>
auto zip(T vals1, U vals2)
{
    auto it1 = vals1.begin();
    auto it2 = vals2.begin();
    for (; vals1.end() != it1 && vals2.end() != it2; ++it1, ++it2)
        co_yield std::make_pair(*it1, *it2);
};
```

SPIN CYCLE

```
for (auto [pos, color] : zip(spiral(), hueCycleGen())) // 1. zip the generators
{
    cv::Point pix = pos + offset;                      // 2. offset to actual pixel
position
    if (img.rows*2 <= pix.x && img.cols*2 <= pix.y)    // 3. no more pixels to scan
        break;
    if (!rect.contains(pix))                           // 4. skip out of bounds
        continue;
    img(pix) = color;                                  // 5. set pixel color
}
```

TREEVERSAL

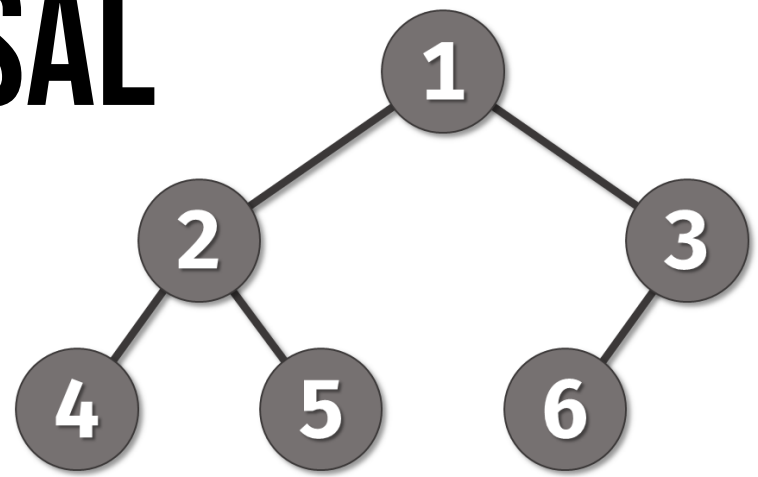



```
class TreeNode
{
   // ...
   using ValueGen = std::experimental::generator<int>;
   ValueGen inorder() //  In-order (Left, Root, Right)
   {
      if (left_)
         for (auto v : left_->inorder()) // iterate on recursion
            co_yield v;
      co_yield val_;
      if (right_)
         for (auto v : right_->inorder())
            co_yield v;
   }

   ValueGen preorder() // Pre-order (Root, Left, Right)
   {
      co_yield val_;
      if (left_)
         for (auto v : left_->preorder())
            co_yield v;
      if (right_)
         for (auto v : right_->preorder())
            co_yield v;
   }

   ValueGen postorder() // Post-order (Left, Right, Root)
   { /* ... */ }
```

```
enum Order { IN_ORDER, PRE_ORDER, POST_ORDER };
auto order(Order order)  // this is NOT a coroutine!
{
   switch (order)
   {
      case IN_ORDER:   return inorder();
      case PRE_ORDER:  return preorder();
      case POST_ORDER: return postorder();
   }
}
```

```
for (auto val : head.order(TreeNode::IN_ORDER))
   std::cout << val << ", ";  // 4, 2, 5, 1, 6, 3
```

TREEVERSAL



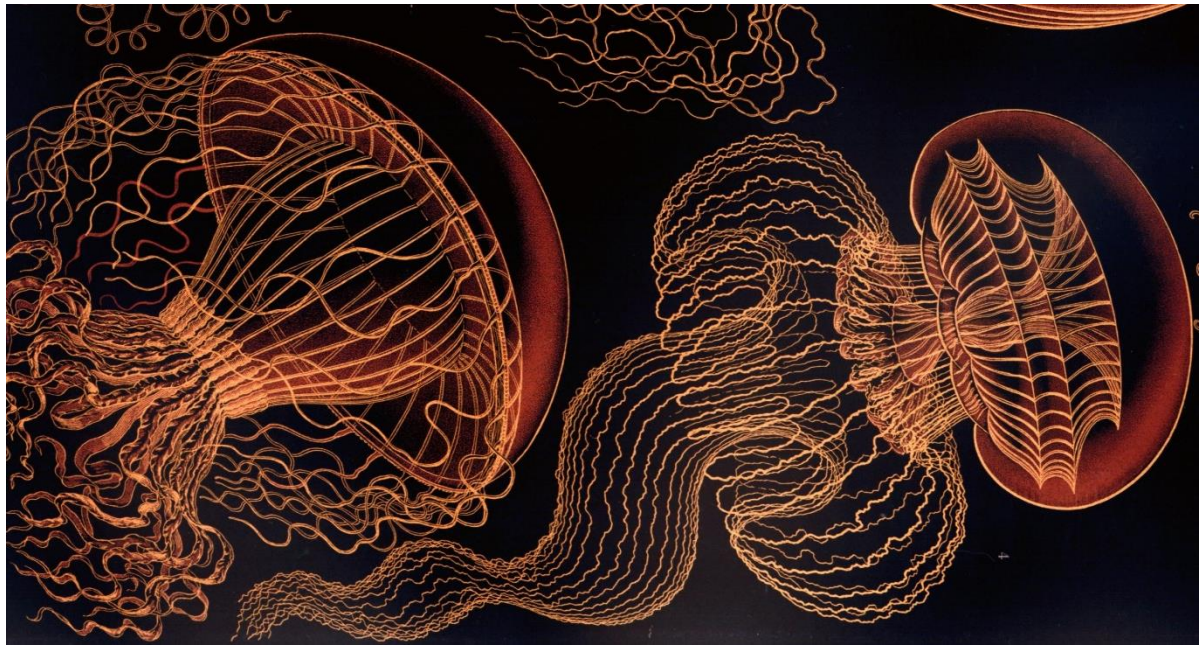

```
class TreeNode
{
   // ...
   using ValueGen = std::experimental::generator<int>;
   ValueGen inorder() //  In-order (Left, Root, Right)
   {
      if (left_)
         for (auto v : left_->inorder()) // iterate on recursion
            co_yield v;
      co_yield val_;
      if (right_)
         for (auto v : right_->inorder())
            co_yield v;
   }

   ValueGen preorder() // Pre-or
   {
      co_yield val_;
      if (left_)
         for (auto v : left_->pr
            co_yield v;
      if (right_)
         for (auto v : right_->preorder())
            co_yield v;
   }

   ValueGen postorder() // Post-order (Left, Right, Root)
   { /* ... */ }
```

```
enum Order { IN_ORDER, PRE_ORDER, POST_ORDER };
auto order(Order order)  // this is NOT a coroutine!
}
```

```
cppcoro::recursive_generator<int> inorder() //  Inorder (Left, Root, Right)
{
   if (left_) co_yield left_->inorder();
   co_yield val_;
   if (right_) co_yield right_->inorder();
}
```

```
for (auto val : head.order(TreeNode::IN_ORDER))
   std::cout << val << ", ";  // 4, 2, 5, 1, 6, 3
```

PITFALLS



- DANGLING REFERENCES
- DECAPITATION
- LIMITATIONS

NOT PERFECT YET

- Beware of temporaries and references
- Pass by value
- Beware of inadvertent execution

DANGLING REFERENCES

- Coroutine execution starts *after* calling `begin()`
- `s` is a ref to temp string which goes out of scope before it is executed!

```
generator<char> explode(const std::string& s)
{
    for (char ch : s)
        co_yield ch;
}

int main()
{
    for (char ch : explode("hello world"))
        std::cout << ch << '\n';
}
```

From blog post by Arthur O'Dwyer bit.ly/2NDSF9G

BOOM!

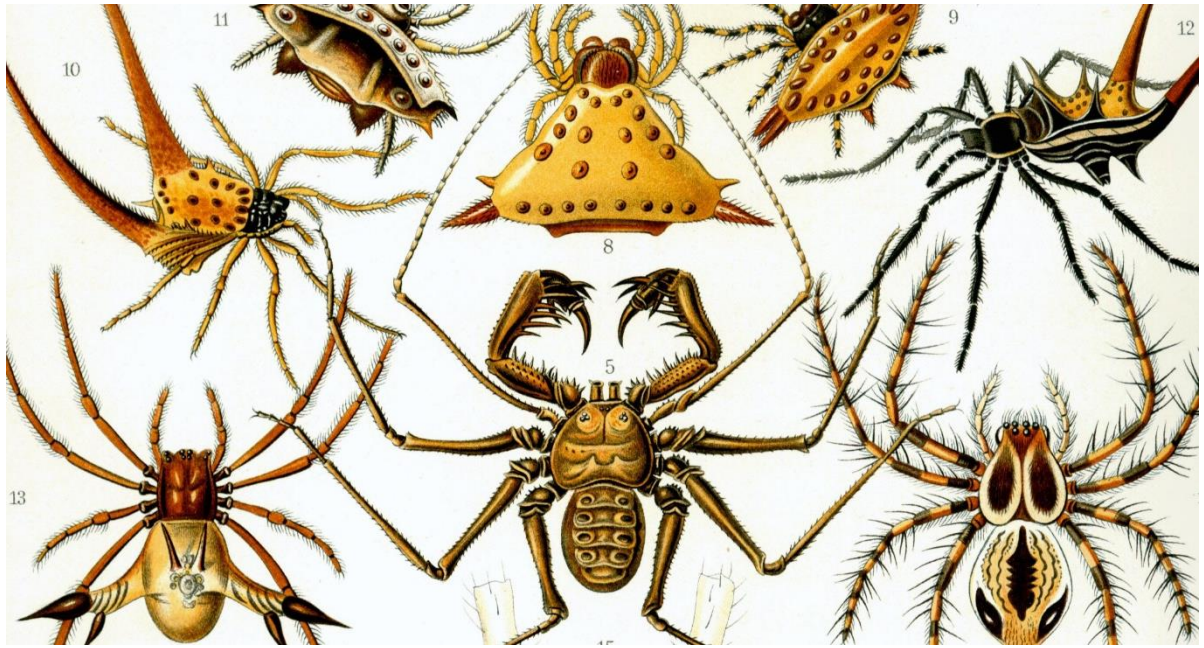
TIP: TAKE COROUTINE ARGUMENTS BY VALUE

DECAPITATION

- Coroutine execution starts after calling `begin()`
- Checking for an empty range (`begin()==end()`) starts execution
- Returning the generator after such a check (with `std::move`) will likely result in skipping the first element.

TIP: BE CAREFUL WHEN HANDLING INITIALLY SUSPENDED COROS

LIMITATIONS



- MISSING FEATURES
- NO STD CORO LIBRARY!
- QOI LIBRARY ISSUES
- QOI COMPILER ISSUES

NOT PERFECT YET

- No plain return statements
- No placeholder return types (auto or Concept)
- constexpr functions, constructors, destructors, and the main function cannot be coroutines

RESOURCES

- A massive, well maintained, list of resources, papers, articles and videos from the diligent MattPD bit.ly/3436zZ3
- en.cppreference.com/w/cpp/language/coroutines
- The `#coroutines` channel on the C++ Slack
- More details on my blog videocortex.io/2019/Brain-Unrolling

THANK YOU!

@adishavit :: videocortex.io