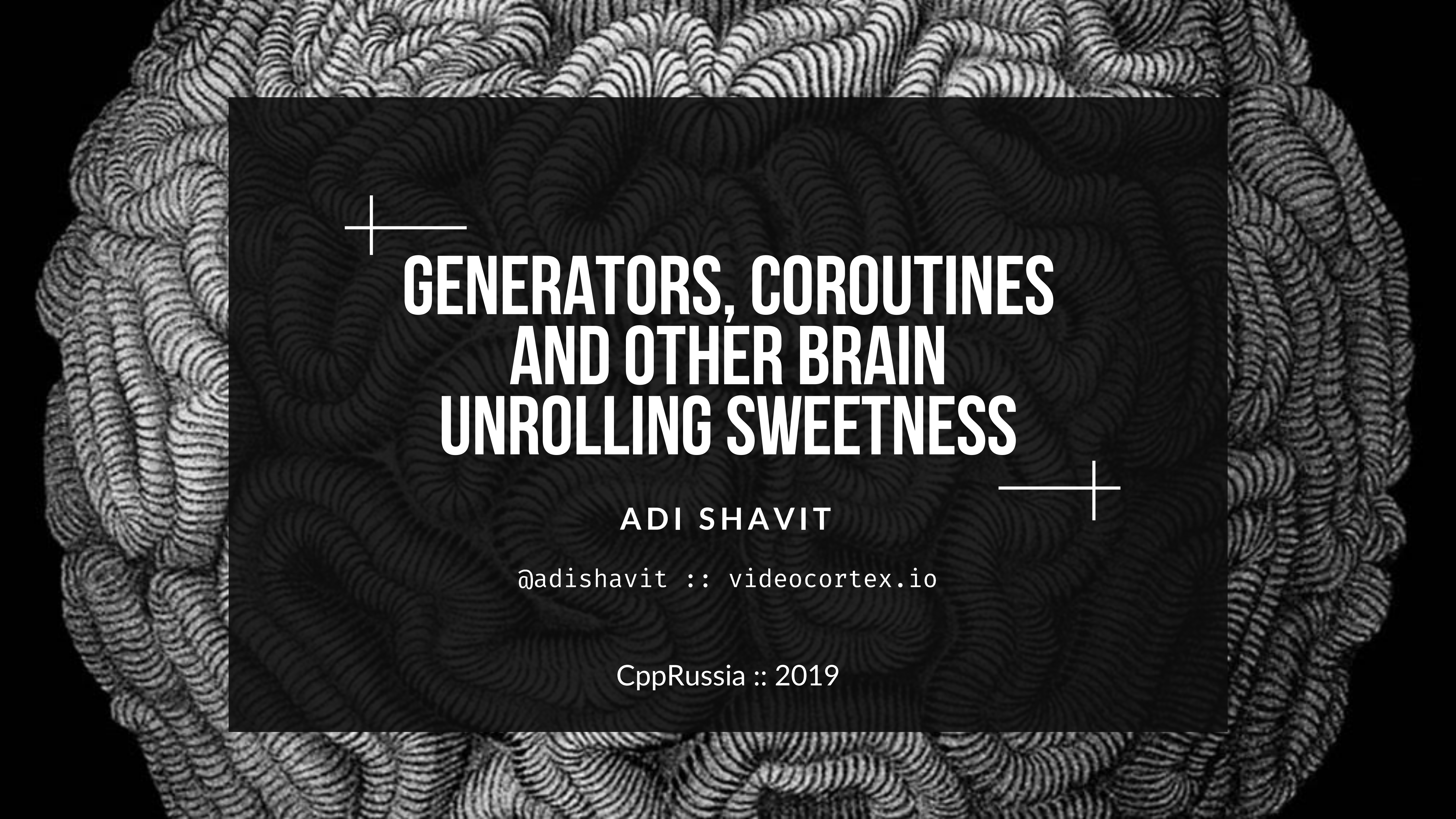
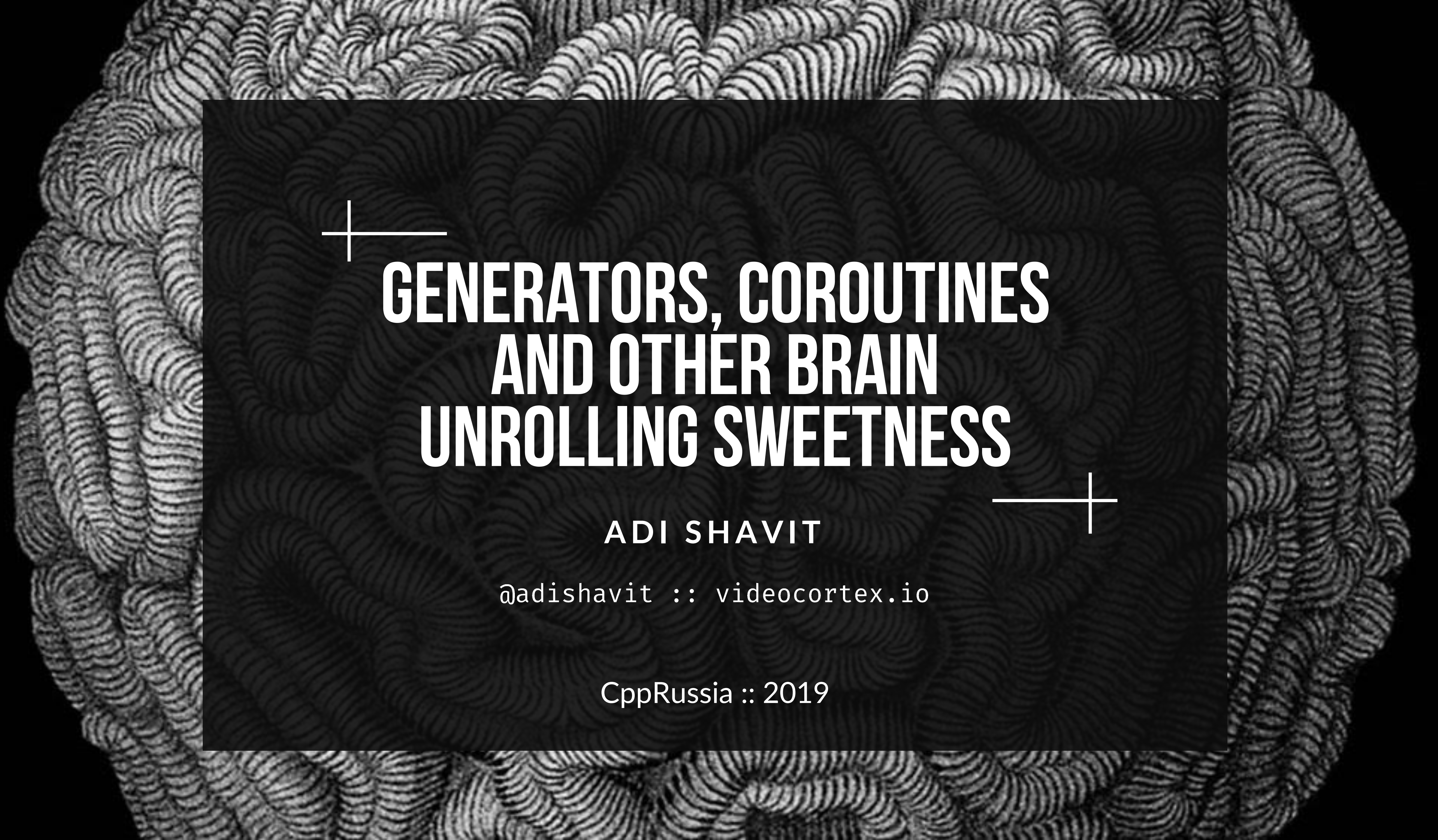


GENERATORS, COROUTINES AND OTHER BRAIN UNROLLING SWEETNESS

ADI SHAVIT

@adishavit :: videocortex.io

CppRussia :: 2019



GENERATORS, COROUTINES AND OTHER BRAIN UNROLLING SWEETNESS

ADI SHAVIT

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FUNCTIONS A.K.A. 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: Sum + Print?

1947

DID YOU KNOW?

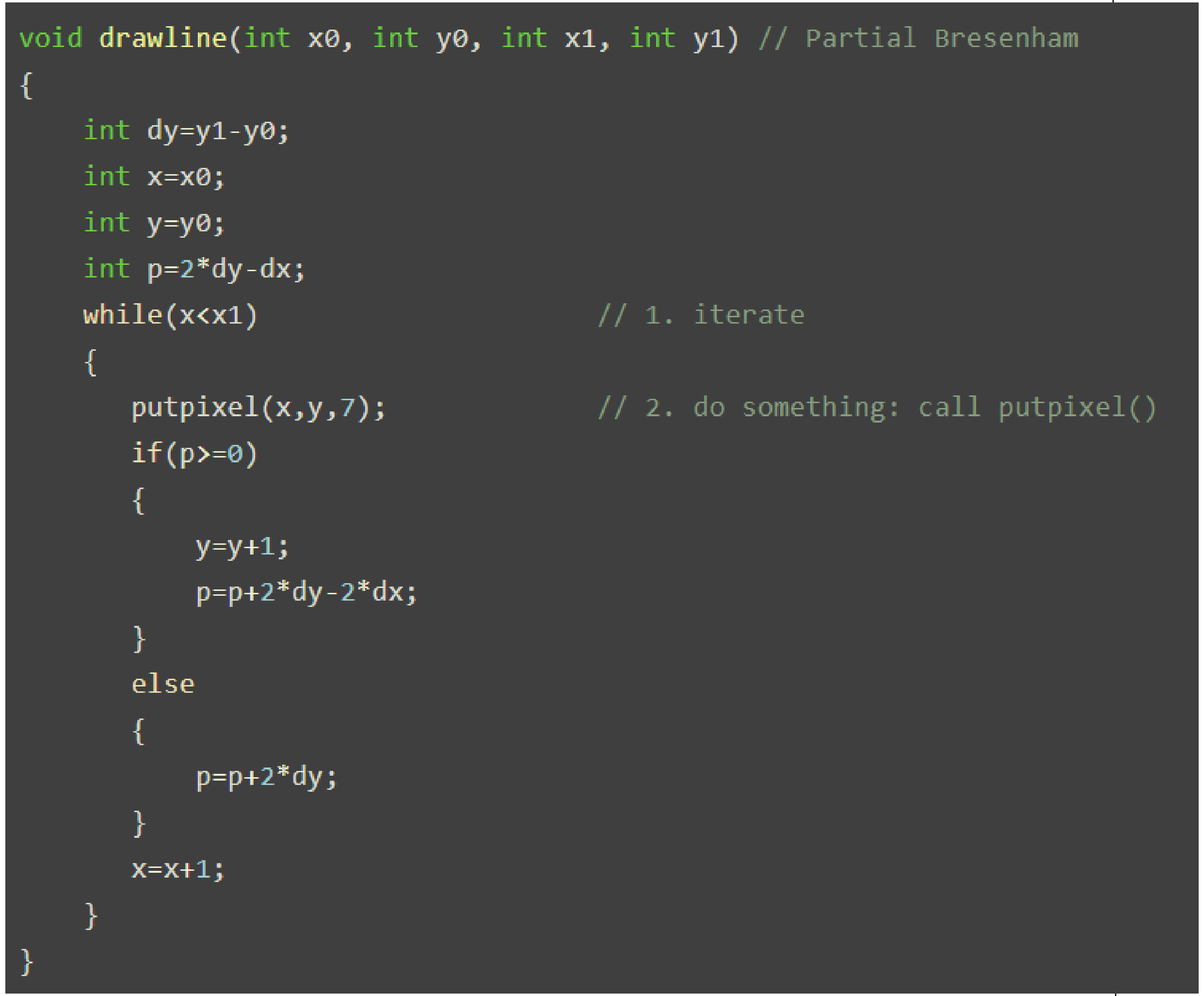
The concept of a function, or sub-routine goes back to one of the first computers, the ENIAC, in the late 1940s and the term sub-routine is from the early 1950s.

FUNCTIONS A.K.A. SUB-ROUTINES

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

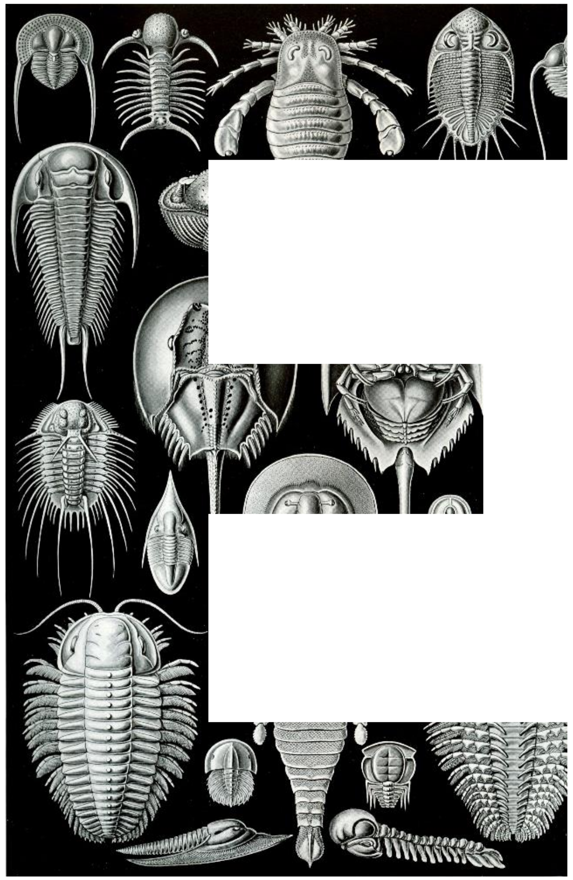
Assumes `putpixel()`

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



```c
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;
    }
}
```

“

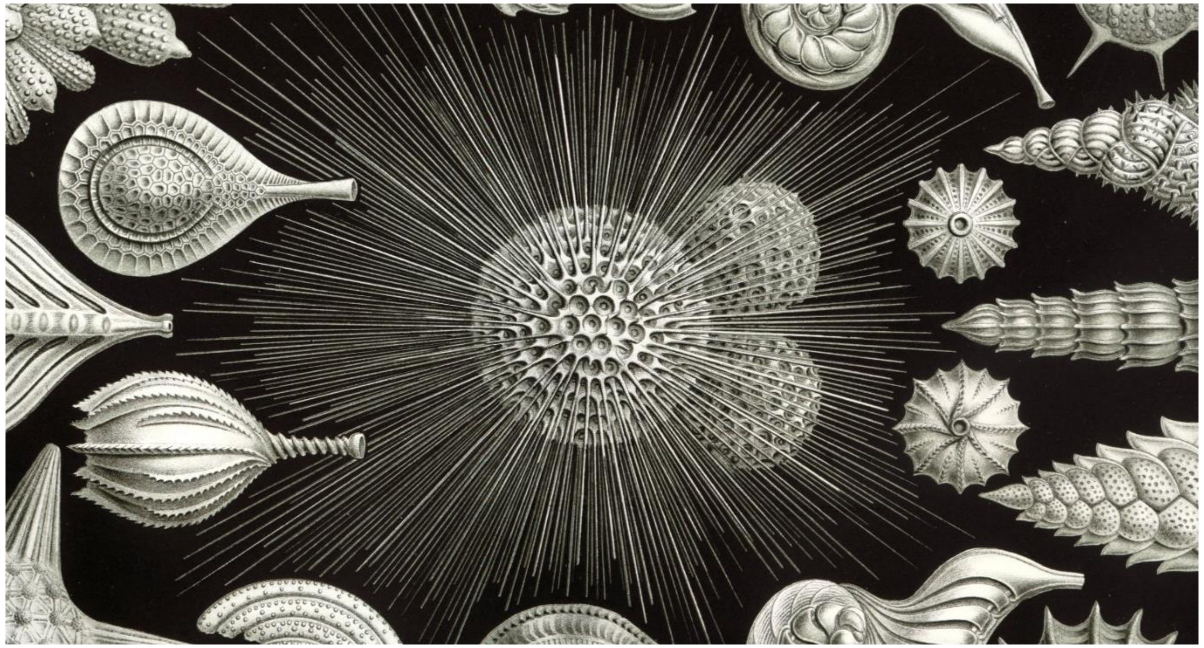


SUBROUTINES ARE EAGER AND CLOSED

EAGER PROCESSING

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

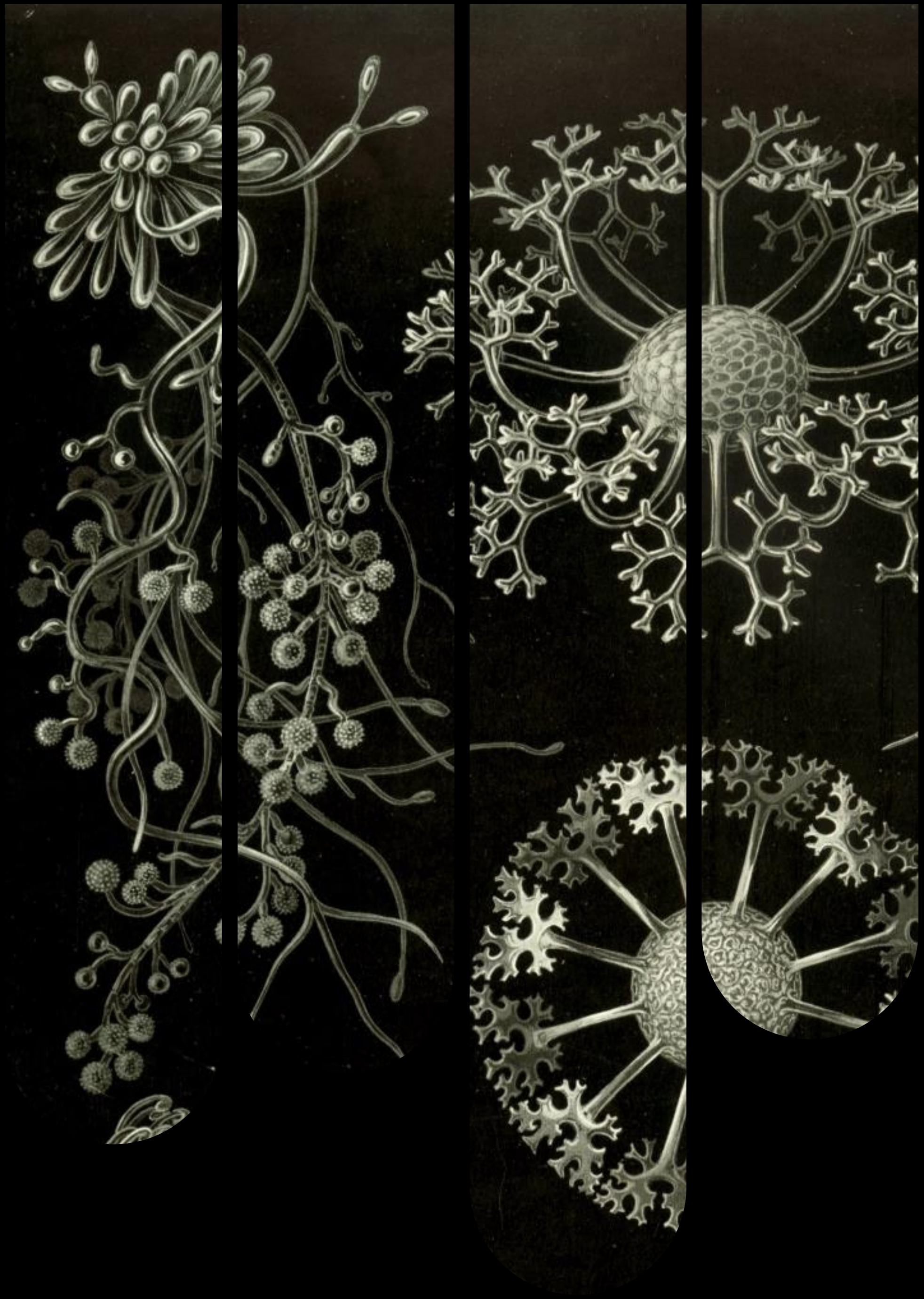
CALLBACKS



- 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

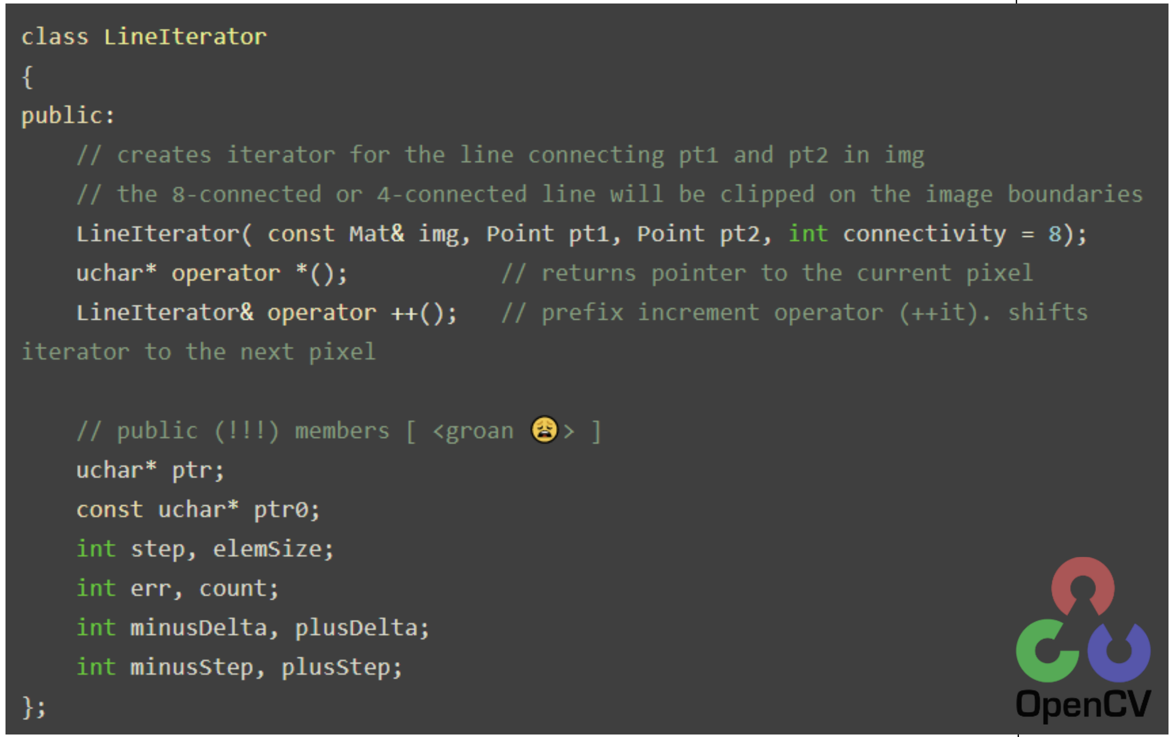
DID YOU KNOW?

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

```cpp
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;
```

```cpp
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

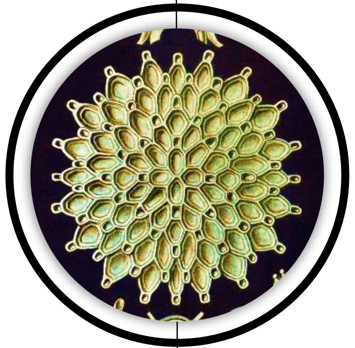
AWKWARD COUPLING

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 makes STL algorithms more powerful by making them composable.
- Create pipelines to transform values

2020

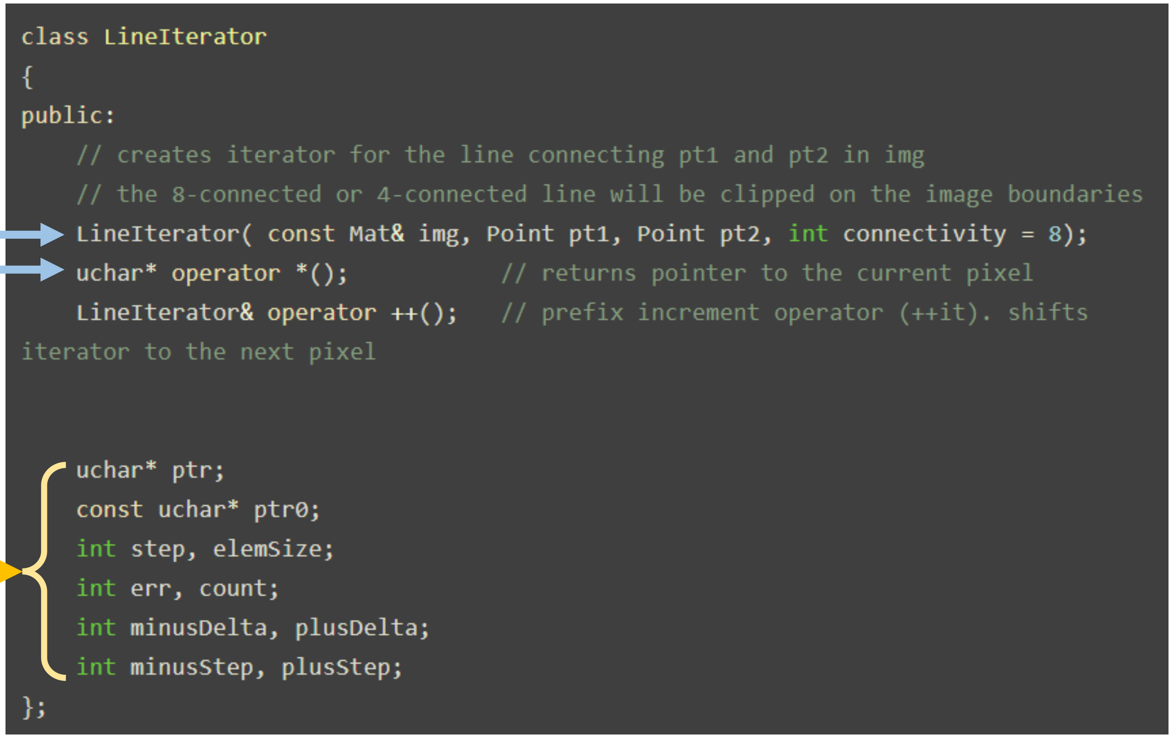
DID YOU KNOW?

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.



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    LineIterator( const Mat& img, Point pt1, Point pt2, int connectivity = 8);
    uchar* operator *();            // returns pointer to the current pixel
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    uchar* ptr;
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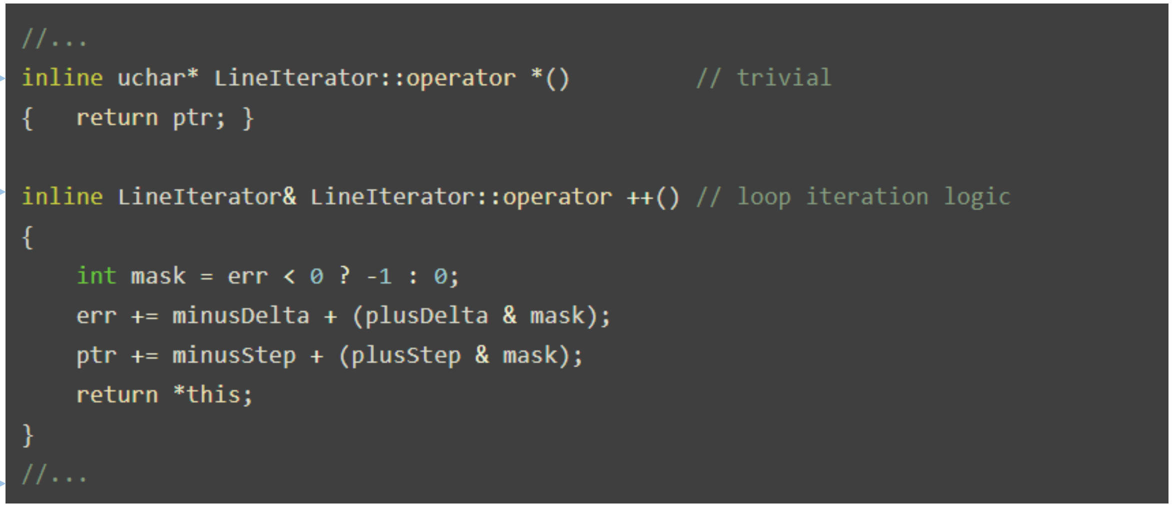
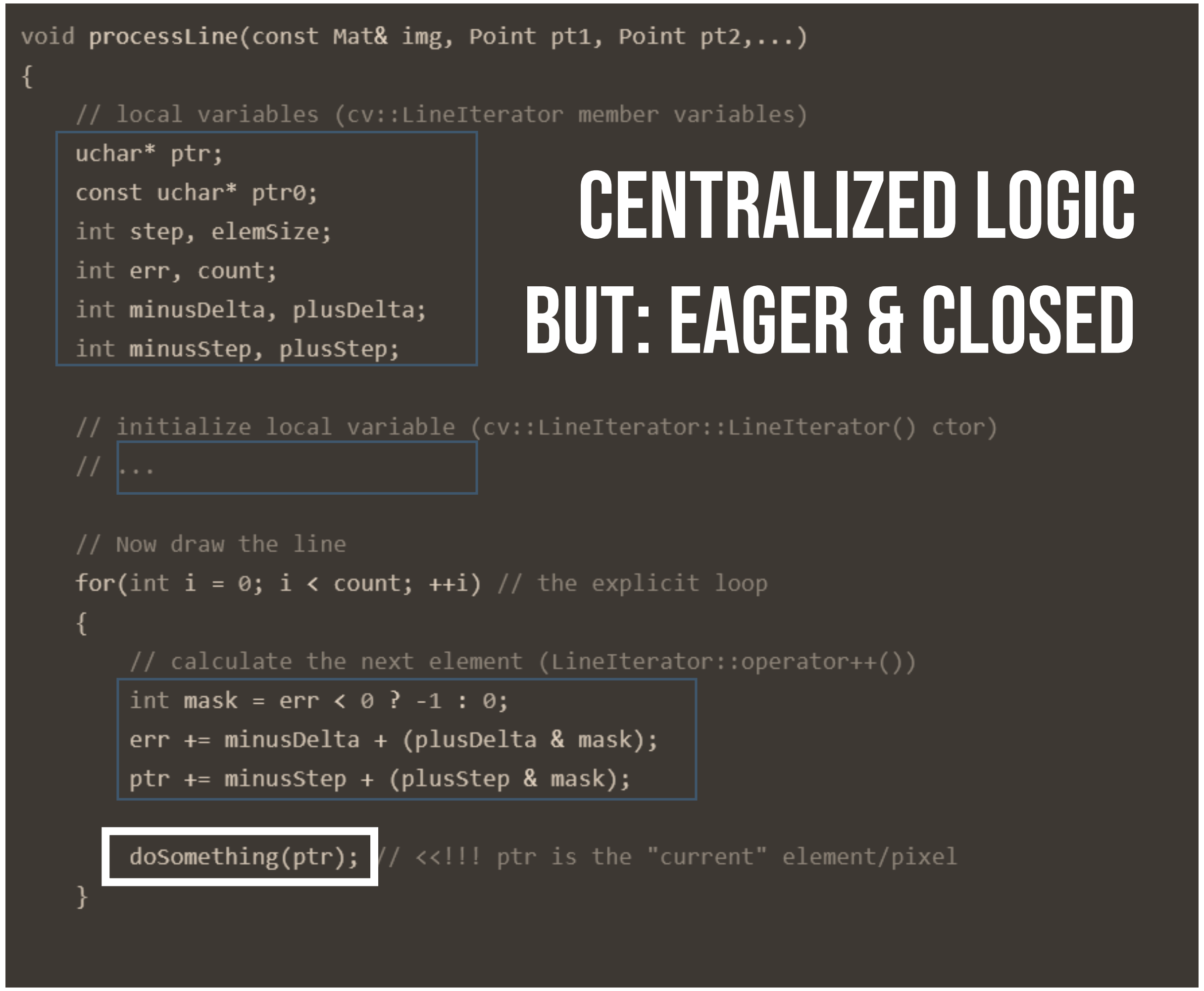
};
```



```
//...
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;

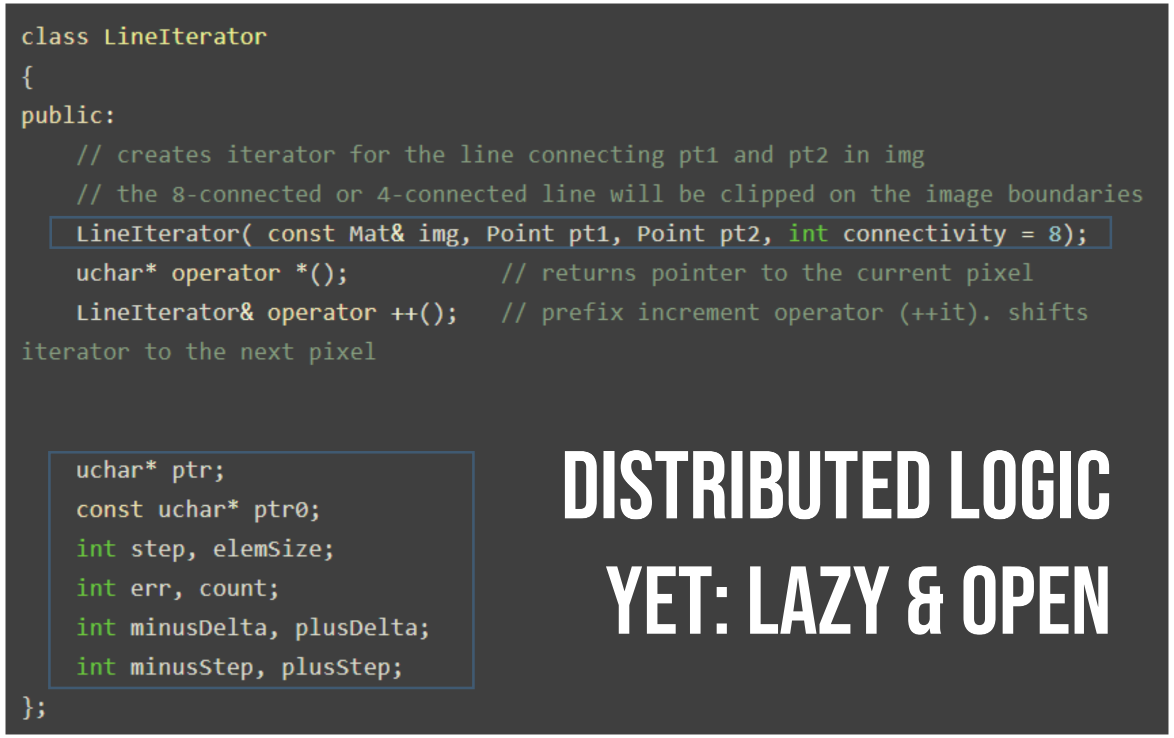
    // initialize local variable (cv::LineIterator::LineIterator() ctor)
    // ...

    // 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

BUT: EAGER & CLOSED



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    uchar* operator *();            // returns pointer to the current pixel
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iterator to the next pixel

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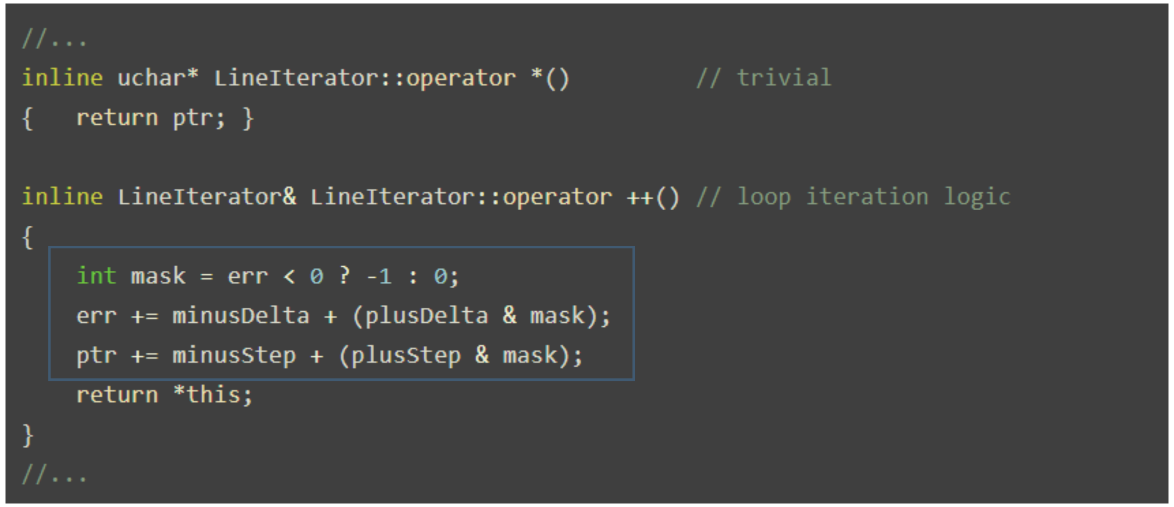

DISTRIBUTED LOGIC

YET: LAZY & OPEN



```
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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. Return an intermediate value;
3. Resume later;
4. Preserve local state;
5. Allows re-entry more than once;
6. Non-pre-emptive → Cooperative

JUST LIKE WHAT WE WANT!

1958

DID YOU KNOW?

The term *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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6. Non-pre-emptive → Cooperative

JUST LIKE WHAT WE WANT!

```
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 certain requirements.

CANNOT TELL COROUTINE FROM FUNCTION BY SIGNATURE

COROUTINES ARE AN "IMPLEMENTATION DETAIL"

2020

DID YOU KNOW?

The data required to resume coroutine 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? **`42`**
- The return type is… **`int`**
- Is it a coroutine? No

THE SIMPLEST CODE

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

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

```cpp
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

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

OR

```
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();
```

INFINITE RANGES

```cpp
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!

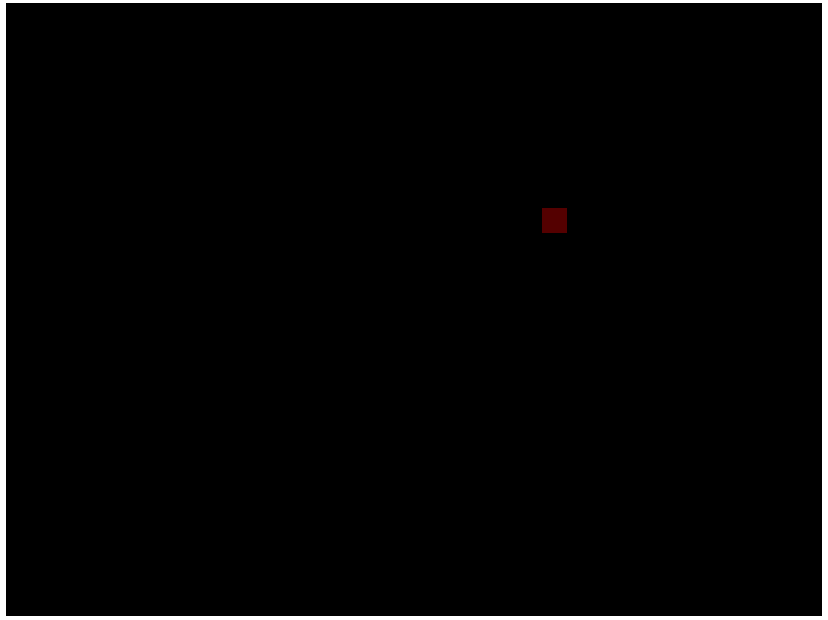
MSVC EXTENSIONS

- 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`

SPIN CYCLE

```cpp
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);
    }
}
```

```cpp
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);
};
```

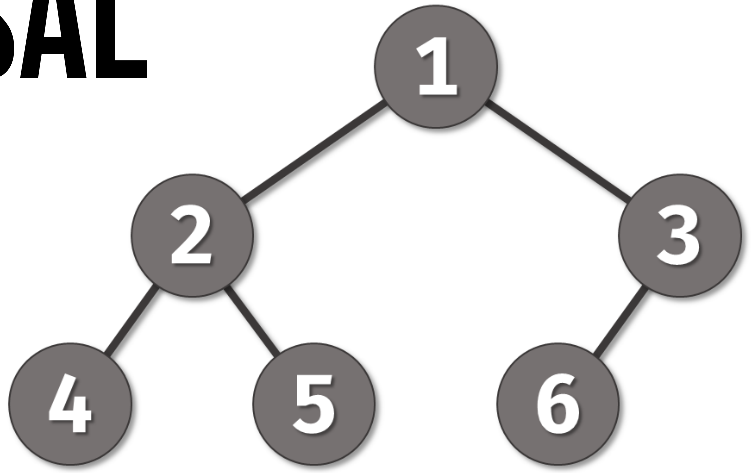
SPIN CYCLE

```
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

```cpp
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)
   { /* ... */ }
```

```cpp
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();
   }
}
```



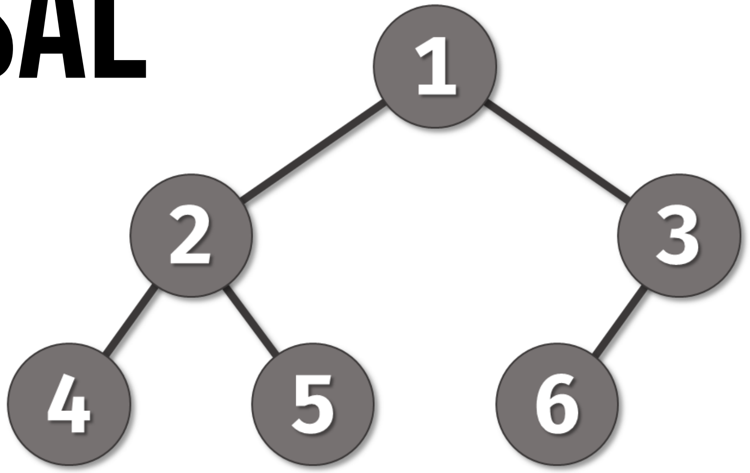
```cpp
for (auto val : head.order(TreeNode::IN_ORDER))
   std::cout << val << ", ";  // 4, 2, 5, 1, 6, 3
```

```
class TreeNode
{
  // ...
  using ValueGen = std::experim
  ValueGen inorder() //  In-ord
  {
    if (left_)
      for (auto v : left_->in
        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!

  }
}
```

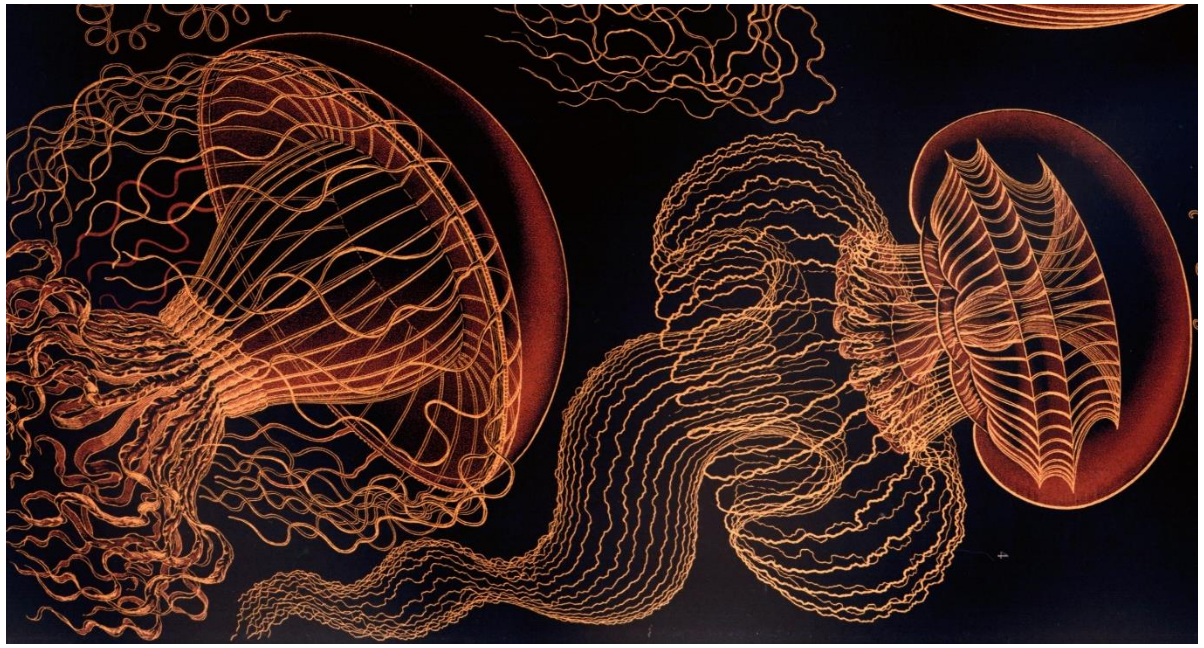
```
cppcoro::recursive_generator<int> inorder() //  Inorder (Left, Root, Right)
{
   if (left_) co_yield left_->inorder();
   co_yield val_;
   if (right_) co_yield right_->inorder();
}
```

TREEVERSAL



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

PITFALLS



- DANGLING REFERENCES
- LIMITATIONS

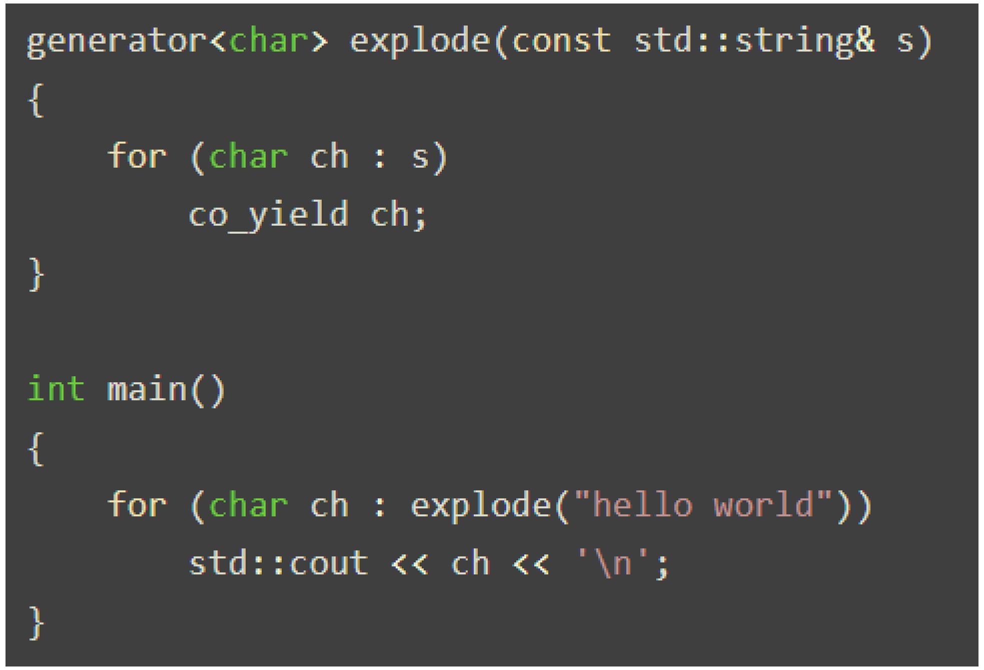
NOT PERFECT YET

- 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!

BOOM!



```
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

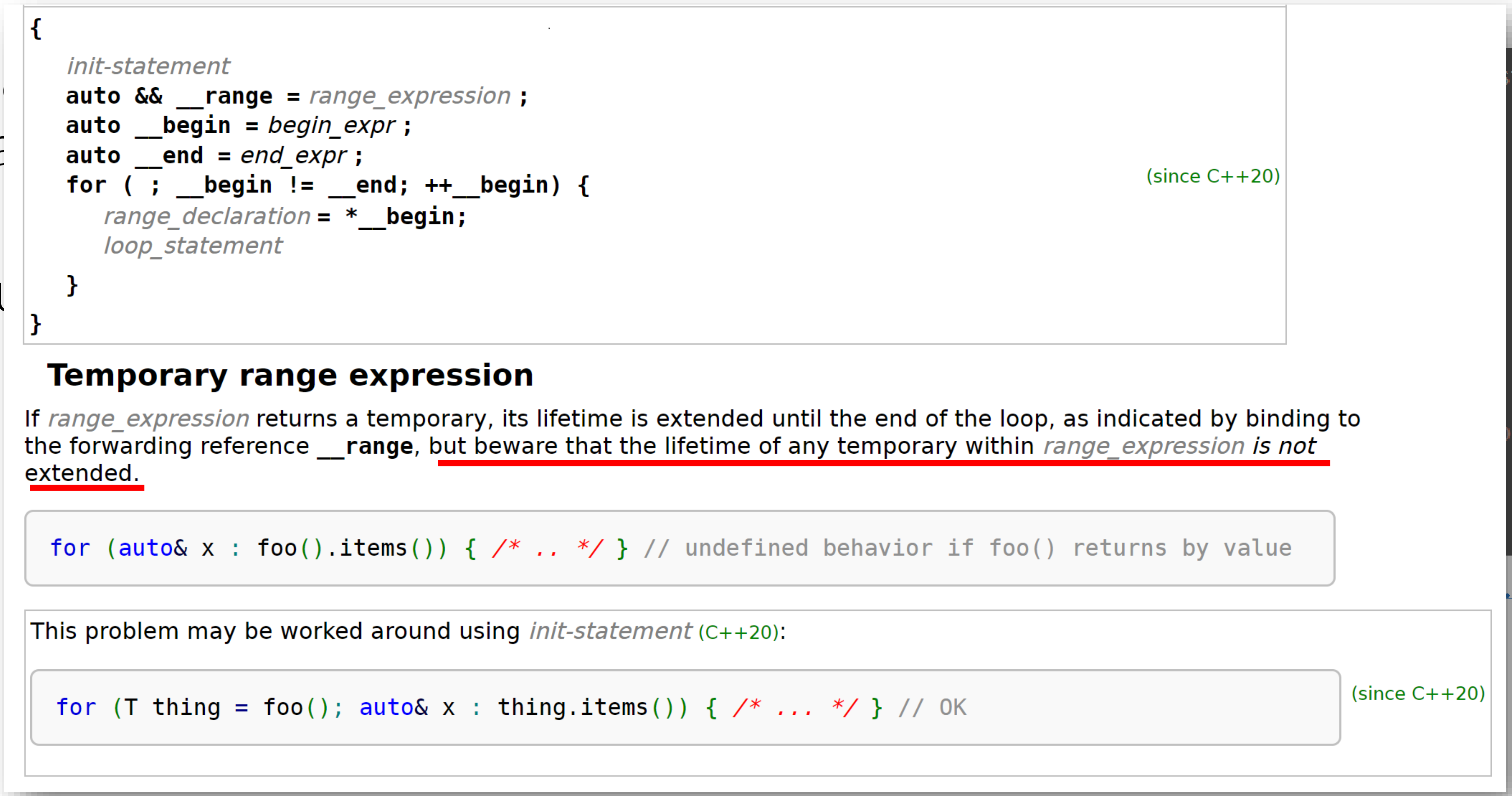
TIP: TAKE COROUTINE ARGUMENTS BY VALUE

DANGLING REFERENCES

- C
  Ca
- S
  Ou

```
tring& s)

rld"))
```

.ly/2NDSF9G



```
{
    init-statement
    auto && __range = range_expression ;
    auto __begin = begin_expr ;
    auto __end = end_expr ;
    for ( ; __begin != __end; ++__begin) {
        range_declaration = *__begin;
        loop_statement
    }
}
```

(since C++20)

Temporary range expression

If *range_expression* returns a temporary, its lifetime is extended until the end of the loop, as indicated by binding to the forwarding reference **__range**, but beware that the lifetime of any temporary within *range_expression is not* extended.

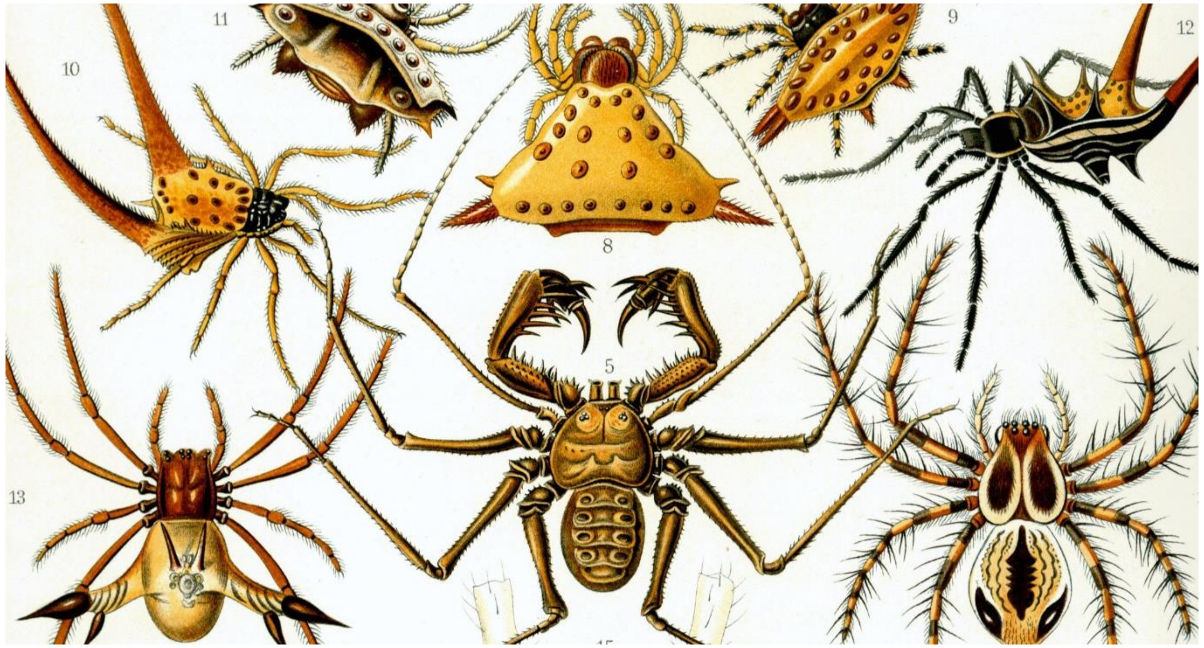
```
for (auto& x : foo().items()) { /* .. */ } // undefined behavior if foo() returns by value
```

This problem may be worked around using *init-statement* (C++20):

```
for (T thing = foo(); auto& x : thing.items()) { /* ... */ } // OK
```

(since C++20)

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 list of coroutine resources, 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

Kunstformen der Natur, Ernst Haeckel :: *Hypebeast* Presentation Template