More Ranges Please

C++North 2024

roi@istraresearch.com

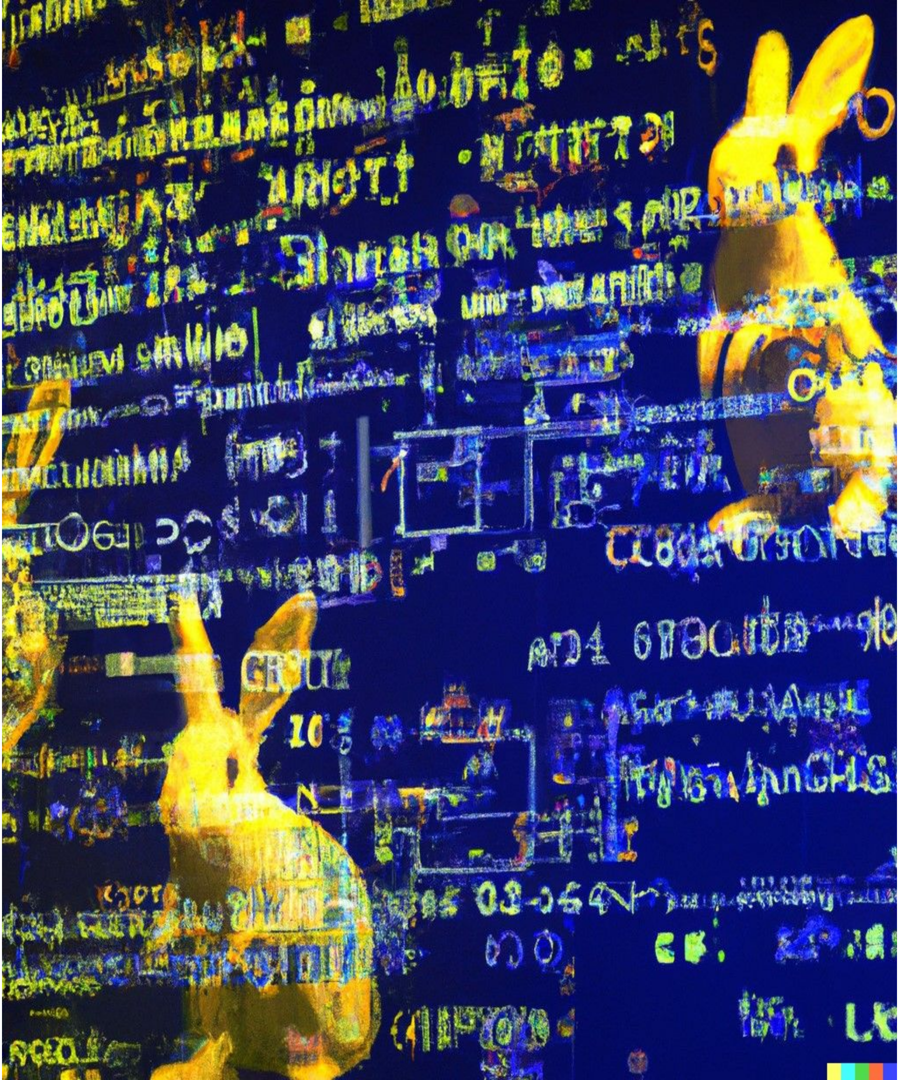
Slides

Hi, I'm Roi

- Roi Barkan (he/him) - רועי ברקן
- I live in Tel Aviv
- C++ developer since 2000
- SVP Development & Technologies @ Istra Research
  - Finance, Low Latency, in Israel
  - careers@istraresearch.com
- Always happy to learn and explore
  - Please - ask questions, make comments

Slides

roi@istraresearch.com



Outline

- Ranges
  - Introduction
  - Strengths, core ideas
  - Review the views
- Libraries
  - What
  - Why
  - How
- Rabbits
- Summary

C++ Ranges

roi@istraresearch.com

Ranges is a Breakthrough Library

- One of C++20 big-four features
- Rests on decades of existing libraries and experience
  - C++98 iterator-based algorithms
  - Fundamentals of functional / vectoric languages (APL, BQN, R, Julia, NumPy) Conor Hoekstra
  - Libraries of similar languages (D, Rust, Java) Barry Revzin.
- Main Innovation - Composability
  - Many algorithms take ranges as input and return ranges as output
    - Opposed to in-place or output-iterator nature of C++98 algorithms
  - Range Adaptors - algorithms encalsupated as ‘lazy ranges’ (views)
    - Algorithms as composable objects - ‘expression templates’
  - Projections - unary transformations of the ranges we inspect.

roi@istraresearch.com

Composability of Ranges

- Chaining algorithms due to range arguments and results

```
ranges::reverse(ranges::search(str,"abc"sv));
```
godbolt

- Views as composable lazy ranges

```
str | views::split(' ') | views::take(2);
```
godbolt

- Views have a value/algorithm duality

```
auto square_evens =
     views::filter([](auto x) { return int(x) % 2 == 0; }) |
     views::transform([](auto x) { return x * x; });
```
godbolt

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The Views in the Standard (C++20/23*/26**)

- Factories/Generators: `empty`, `single`, `iota`, `repeat*`, (`std::generator*`)
- Rank preserving: `all`, `filter`, `transform`, `take{_while}`, `drop{_while}`, `reverse`, `stride*`, `adjacent_transform*`, (`counted`)
- Rank preserving - variadic→tuples: `zip*`, `cartesian_product*`
- Rank decreasing - tuples: `elements`, `keys`, `values`
- Rank decreasing - variadic: `zip_transform*`, `concat**`
- Rank decreasing - ranges: `join{_with*}`
- Rank increasing - tuples: `enumerate*`, `adjacent*`
- Rank increasing - ranges: `{lazy_}split`, `slide*`, `chunk{_by}*`
- Committee plan for C++26 is in P2760

Factories / Generators

```
namespace stdv = std::views;


stdv::empty<char>                          //=> []
stdv::single('+')                          //=> ['+']
stdv::iota(2,5)                            //=> [2, 3, 4]
stdv::repeat(0.3,3)                        //=> [0.3, 0.3, 0.3]
```

godbolt

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Rank Preserving - 1/2

```
auto not5 = [](int i){return i != 5;};
auto mult2 = [](int i){return i * 2;};
auto iota2_10 = stdv::iota(2,10);

iota2_10 | stdv::all               //=> [2, 3, 4, 5, 6, 7, 8, 9]
iota2_10 | stdv::filter(not5)      //=> [2, 3, 4, 6, 7, 8, 9]
iota2_10 | stdv::transform(mult2) //=> [4, 6, 8, 10, 12, 14, 16, 18]
iota2_10 | stdv::take(6)           //=> [2, 3, 4, 5, 6, 7]
iota2_10 | stdv::drop(6)           //=> [8, 9]
```

godbolt

Rank Preserving - 2/2

```
auto not5 = [](int i){return i != 5;};
auto iota2_10 = stdv::iota(2,10);

iota2_10 | stdv::take_while(not5)      //=> [2, 3, 4]
iota2_10 | stdv::drop_while(not5)      //=> [5, 6, 7, 8, 9]
iota2_10 | stdv::reverse               //=> [9, 8, 7, 6, 5, 4, 3, 2]
iota2_10 | stdv::stride(3)             //=> [2, 5, 8]
iota2_10 | stdv::adjacent_transform<2>(std::plus{})
                                       //=> [5, 7, 9, 11, 13, 15, 17]
```

[godbolt]()

Rank Preserving - Variadic ⇒ Tuples

```
auto iota2_7 = stdv::iota(2,7);
auto iota2_4 = stdv::iota(2,4);
auto iota6_9 = stdv::iota(6,9);

stdv::zip(iota2_7, iota6_9)                    //=> [(2, 6), (3, 7), (4, 8)]

stdv::cartesian_product(iota2_4, iota6_9)  //=> [(2, 6), (2, 7), (2, 8),
                                                  (3, 6), (3, 7), (3, 8)]
```

godbolt

roi@istraresearch.com

Rank Decreasing - Tuples

```
auto the_zip = stdv::zip(iota2_7, iota6_9, "abcdef"sv);
                                //=> [(2, 6, 'a'), (3, 7, 'b'), (4, 8, 'c')]

the_zip | stdv::keys           //=> [2, 3, 4]
the_zip | stdv::values         //=> [6, 7, 8]
the_zip | stdv::elements<2> //=> ['a', 'b', 'c']
```

godbolt

roi@istraresearch.com

Rank Decreasing - Variadic

```
auto iota2_7 = stdv::iota(2,7); auto iota6_9 = stdv::iota(6,9);
stdv::zip(iota2_7, iota6_9)                 //=> [(2, 6), (3, 7), (4, 8)]

stdv::zip_transform(iota2_7, iota6_9, std::multiplies{})
                                            //=> [12, 21, 32]
stdv::concat(iota2_7, iota6_9)              //=> [2, 3, 4, 5, 6, 6, 7, 8]
```

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roi@istraresearch.com

Rank Decreasing - Ranges

```
vector{"hey"sv, "C++"sv} | stdv::join
                                    //=> ['h', 'e', 'y', 'C', '+', '+']
(vector{"hey"sv, "C++"sv} | stdv::join_with(':'))
                                    //=> ['h', 'e', 'y', ':', 'C', '+', '+]
```

godbolt

Rank Increasing - Tuples

```
"hey"sv | stdv::enumerate
                 //=> [(0, 'h'), (1, 'e'), (2, 'y')]
"hello"sv | stdv::adjacent<3>
                 //=> [('h', 'e', 'l'), ('e', 'l', 'l'), ('l, 'l', 'o')]
```

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roi@istraresearch.com

Rank Increasing - Ranges

```
"hey C++"sv | stdv::split(' ')  //=> [['h', 'e', 'y'], ['C', '+', '+']]
"hey C++"sv | stdv::lazy_split(' ')
                                //=> [['h', 'e', 'y'], ['C', '+', '+']]
"hello"sv | stdv::slide(3)      //=> [['h', 'e', 'l'], ['e', 'l', 'l'],
                                      ['l, 'l', 'o']]
"hey C++"sv | stdv::chunk(3)    //=> [['h', 'e', 'y'], [' ', 'C', '+'],
                                      ['+']]
"hello C++"sv | stdv::chunk_by(equal_to{})
 //=> [['h'], ['e'], ['l', 'l'], ['o'], [' '], ['C'], ['+', '+']]
```

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roi@istraresearch.com

Libraries

roi@istraresearch.com

What is a Library

- Code for coders
- Self contained reusable software
- Abstraction layer
- Language within a programming language
    - Domain specific language (DSL)
- Building blocks
- Simple interface (API) with tricky implementation
- Vocabulary
- …

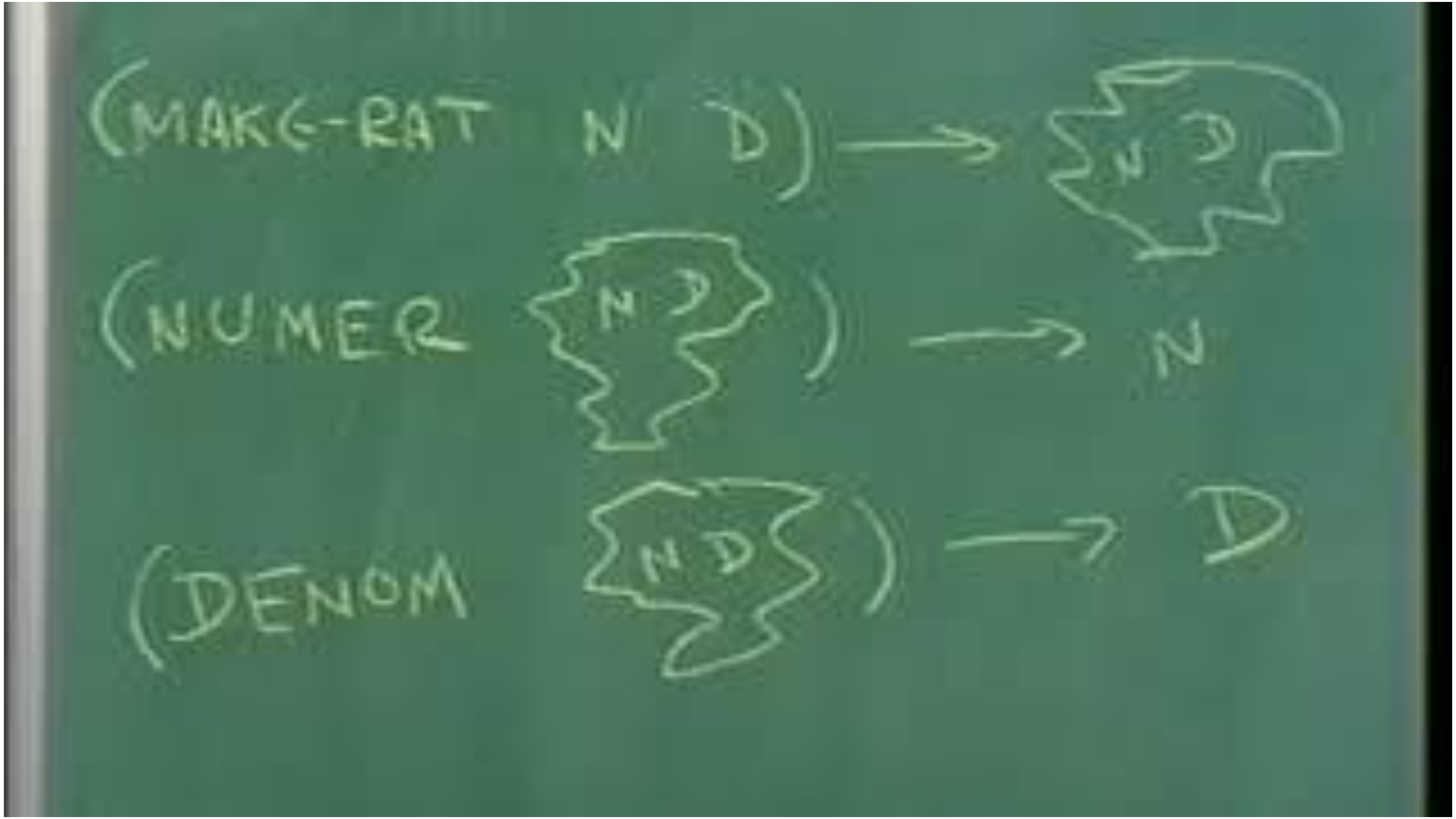
roi@istraresearch.com

Clip

SICP

link

Abelson, Sussman, Sussman 1984



Why Should We Write Libraries

- Reuse: don't repeat yourself (DRY)
- Vocabulary: raise the level of discussion
- Building blocks:
  - The higher we go - change is more likely (close to users)
  - The lower we go - more stable, potentially robust.
- Abstraction layers:
  - Complexity is safer when it's well encapsulated
  - Lower level likely better defined (pre/post-conditions)
  - Lower level is typically more testable.
- Libraries can be stacked / composed.

Sean Parent's Vision

A (New) Possible Future

- A large library of proven generic components
- A small number of non-Turing complete declarative *forms* for assembling the generic components

Adobe 41

[All the Safeties C++Now 2023]

roi@istraresearch.com

How to Write Libraries

- Start with algorithms (Christopher Di Bella, Eric Niebler)
  - Write the code that you need
  - Generalize, distill, *simplify*
  - Concepts will emerge from the *generic* attributes you find.
- Pay attention to the API - the abstraction layer
  - Easy to use, hard to misuse (Ben Deane)
  - Consider preconditions and postconditions
  - Return every potentially useful piece of information (Stepanov).
- Aim for *regular*, *algebraic* data types
  - Value semantic objects typically behave well in the language
  - Do you have a *group?*, a *monoid?*, a *monad*?

Finding Algorithms

- Algorithms are everywhere
  - Not just in CS textbooks
- Can be found in many places
  - Other languages
  - Other libraries
  - Research papers
  - Your own codebase

Clip

Stepanov on Science

[link]

STL and its Design Principles 2002

roi@istraresearch.com

More From Stepanov

link

roi@istraresearch.com

More Ranges

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First Inspiration - Hondt Method

- Credit to Tina Ulbrich - How to Rangify Your Code
- Hondt method - assigning parliament seats in a party-voting democracy

	party 1 votes: 110		party 2 votes: 85		party 3 votes: 35	
1	(1)	110 / 1 = 110	(2)	85 / 1 = 85	(6)	35 / 1 = 35
2	(3)	110 / 2 = 55	(4)	85 / 2 = 42.5		35 / 2 = 17.5
3	(5)	110 / 3 = 36.66	(7)	85 / 3 = 28.33		35 / 3 = 11.66
4		110 / 4 = 27.5		85 / 4 = 21.25		35 / 4 = 8.75
5		110 / 5 = 22		85 / 5 = 17		35 / 5 = 7
6		110 / 6 = 18.33		85 / 6 = 14.16		35 / 6 = 5.83
7		110 / 7 = 15.71		85 / 7 = 12.14		35 / 7 = 5
	seats: 3		seats: 3		seats: 1	

	party 1 votes: 110		party 2 votes: 85		party 3 votes: 35	
1	(1)	110 / 1 = 110	(2)	85 / 1 = 85	(6)	35 / 1 = 35
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5		110 / 5 = 22		85 / 5 = 17		35 / 5 = 7
6		110 / 6 = 18.33		85 / 6 = 14.16		35 / 6 = 5.83
7		110 / 7 = 15.71		85 / 7 = 12.14		35 / 7 = 5
	seats: 3		seats: 3		seats: 1	

Basic Hondt Approach

- Calculate cells and sort them

```
std::ranges::sort(proportional_votes, [](const auto& rhs, const auto& lhs)
{
    return rhs.proportion > lhs.proportion;
});
proportional_votes.resize(total_number_of_seats);
```

- Key observations for P parties and S seats:
  - `sort()` requires eager evaluation and storage of S*P cells
  - `resize()` implies we are sorting too much - `nth_element()` requires O(SP) average steps
  - Each column is already sorted - we can `merge()`
    - Complexity can go down to O(SlogP)
    - `merge()` allow lazy evaluation - a range-view won't need pre-computation/allocation

roi@istraresearch.com

Rabbit 1 - Views for Sorted Ranges

- Suggestion - views for **`merge`**, **`set_union`**, **`set_intersection`**, **`set_{symmetric_}difference`**
  - Most algorithms can benefit from multi-input implementations
  - Heap (**`priority_queue`**) is needed for efficient **`set_union, merge, ....`**
- STL contains several algorithms for sorted ranges: **`{inplace_}merge`**, **`includes`**, **`set_{union,intersection,{symmetric_}difference}`**
  - Also search algorithms: **`{upper,lower}_bound`**, **`equal_range`**, **`(unique)`**.
- All the operations are lazy in nature
- Ranges-v3 has views for **`set_{union,intersection,{symmetric_}difference}`** with 2 input ranges
- D-lang has merge and multiWayMerge.

roi@istraresearch.com

Thoughts on Sorted Ranges (Rabbit 2)

- `equal_range`, `unique` can also be views - they have the right signature
- Search can also become filtering views for random-access ranges
  - `take_until(value)`, `drop_until(value)` with O(logN) cost to cache the cut-off
    - Technically `take_until` mostly needs this to stay random-access.
  - `take_between(min,max)` can be more efficient than separate searches.
- If we'll have many algorithms specifically for sorted ranges, we might want a concept, which can also provide the comparator (`value_comp`)
  - D has it, as well as isSorted and assumeSorted factories.
- Simple combinations can be good for vocabulary:

```
auto histogram =
   views::chunk_by(std::equals{}) |
   views::transform([](const auto& rng) {
      return make_pair(begin(rng),distance(rng));});
```

roi@istraresearch.com

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roi@istraresearch.com

Digression - Algorithm Selection

- Sometimes the same goal can be achieved in several ways
  - `ranges::distance` - returns the distance between the beginning and end of a range
  - `ranges::ssize` - returns a signed integer equal to the size of a range
  - `ssize` only works for ranges that have constant-time calculation (opt-out semantic concept); `distance` allows linear calculation. [Ben Deane recommends it].
- The library uses concepts to constrain which ranges are applicable for which algorithm/view, and to know the best method of reaching the intended goal
- Before C++20 other mechanisms were used to achieve this goal - and with concepts we have a way to be more precise and more flexible where needed.

roi@istraresearch.com

Breaking Sort Apart

- Inspired by the R standard library
- `sort()` is O(NlogN) in two aspects:
  - Comparisons (+projections)
  - `iter_swap` operations.
- Sometimes `iter_swap` is much more expensive than comparison
  - For example - sorting rows of a table by one column
  - Projections stress the potential difference between the objects in question.
- Suggested algorithm: `order()` - generate the sorting *permutation*
  - Requires allocating N indexes, and O(NlogN) comparisons
  - Then, *apply* the permutation with N `iter_swap` operations
  - Implementation is likely a one-liner using `iota()` and projections.

roi@istraresearch.com

Rabbit 3 - Permutations

- Permutations allow more flexibility, not just intermediary step:
  - Can be reversed, to regain the original order
  - Can be lazily applied (be range views) - no swaps required.
- Iterator adapters that lazily apply permutations exist in boost, thrust.
- The standard library has other algorithms that deal with permutations.
- Potentially, there might be room for a `permutation`, or `permutation_of<Range>` concept.

roi@istraresearch.com

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Summary

- The C++ ranges library is an exemplar of composability
- Libraries can make software better, safer and cleaner
- Potential libraries are all around us - it’s not just the STL or written by others
- Even C++ ranges might be improved/enhanced in novel ways
- “Go catch rabbits”

- Thank you !!
  - Questions and comments are welcome
  - Thanks to Bryce Lelbach for review and comments

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roi@istraresearch.com

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