

# A new implementation for std::sort

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# Agenda

- Introsort
- BlockQuickSort
- Reinforcement Learning-based Small Sort

# Prior Implementation

```
void __sort(__first, __last, __comp)
{
    while (true)
    {
        // Sort small lengths and break from the loop
        .
        .
        .
        // Choose pivot
        .
        .
        .
        // Partition the current range into two parts around the pivot
        while (true) {
            // Find next two elements to swap and swap them
        }
        // sort one partition recursively, the other iteratively
    }
}
```

# Prior Implementation

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        // Choose pivot
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        // Partition the current range into two parts around the pivot
        while (true) {
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# Prior Implementation

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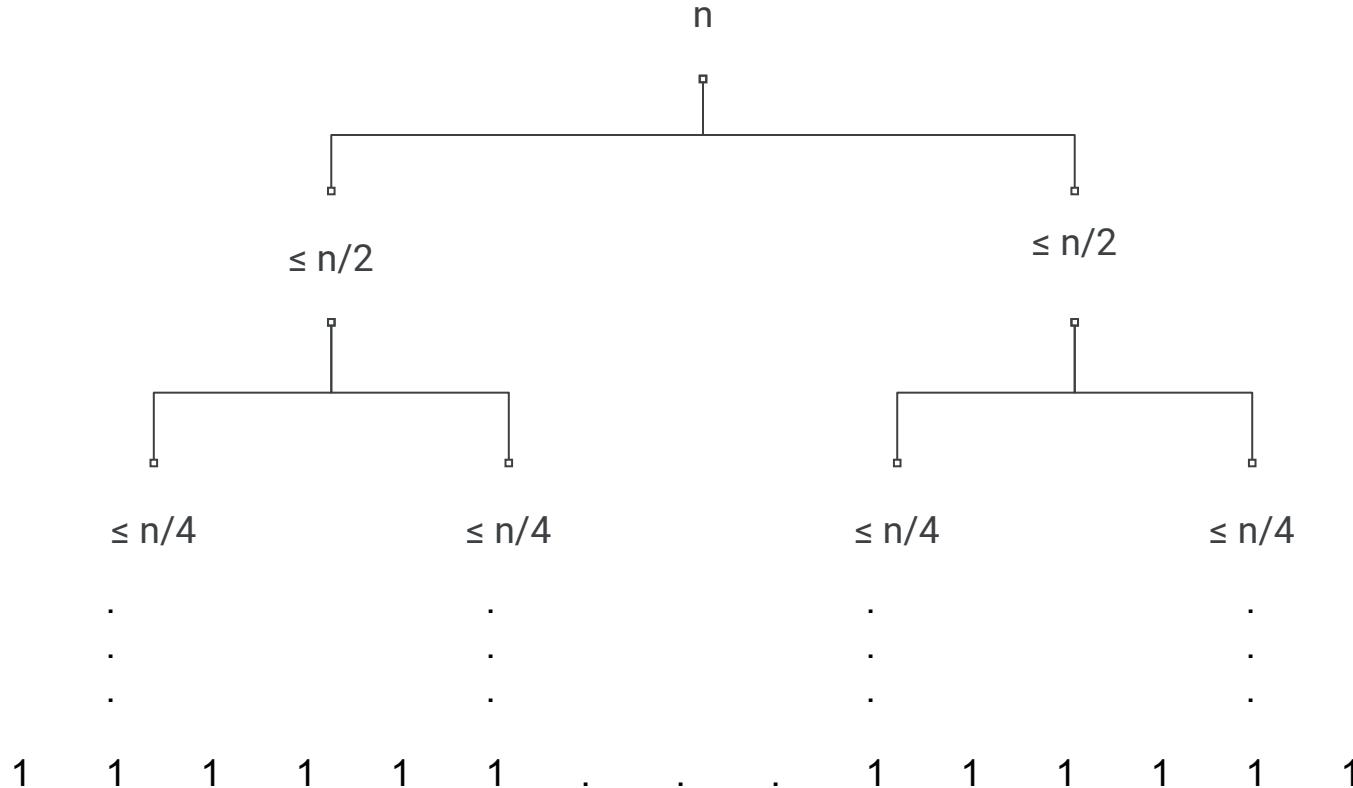
        .

        .

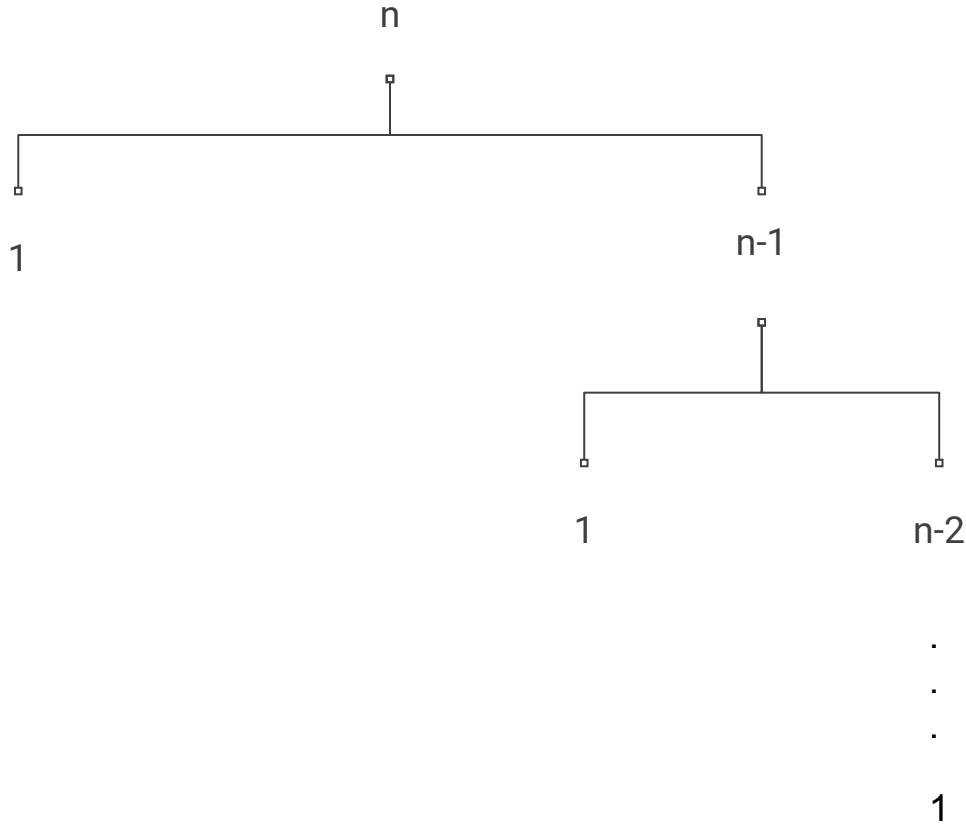
        // Partition the current range into two parts around the pivot
        while (true) {
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        }
        // sort one partition recursively, the other iteratively
    }
}
```

# Introsort

# Quicksort: best case

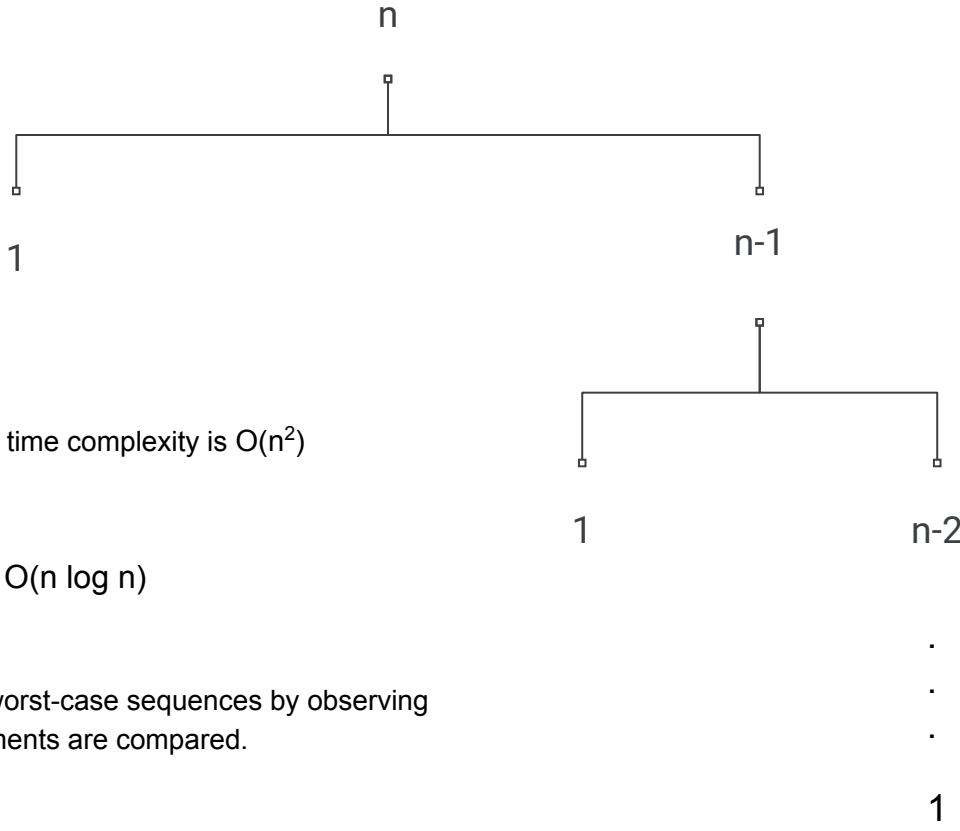


# Quicksort: worst case



# Quicksort: worst case

- Quicksort's worst-case time complexity is  $O(n^2)$
- C++ standard requires  $O(n \log n)$
- Possible to construct worst-case sequences by observing the order in which elements are compared.



# Improve the worst case: Introsort

```
void __introsort(__first, __last, __comp, __depth)
{
    while (true) {
        if (__depth == 0) {
            // Fallback to heap sort as Introsort suggests.
            _VSTD::__partial_sort<__Compare>(__first, __last, __last);
            return;
        }
        --__depth;
        // Same sorting algorithm as shown earlier.
    }
}
```

# Improve the worst case: Introsort

```
void __introsort(__first, __last, __comp, __depth)
{
    while (true) {
        if (__depth == 0) {
            // Fallback to heap sort as Introsort suggests.
            _VSTD::__partial_sort<__Compare>(__first, __last, __last);
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        // Same sorting algorithm as shown earlier.
    }
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```

# Improve the worst case: Introsort

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            _VSTD::__partial_sort<__Compare>(__first, __last, __last, __comp);
            return;
        }
        --__depth;
        // Same sorting algorithm as shown earlier.
    }
}
```

# Microbenchmark Results

Benchmark	Sorting time per element (ns)	
	Quicksort	Introsort
BM_Sort_uint32_QuickSortAdversary_64	33	45
BM_Sort_uint32_QuickSortAdversary_256	132	69
BM_Sort_uint32_QuickSortAdversary_1024	498	118
BM_Sort_uint32_QuickSortAdversary_16384	3846	175
BM_Sort_uint32_QuickSortAdversary_262144	61431	210

# BlockQuickSort

# Branches in Quicksort

```
// Choose pivot  
// Partition the current range into two parts around the pivot  
while (true) {  
    while (__comp(*++__i, *__pivot));  
    while (!__comp(*--__j, *__pivot));  
    if (__i > __j) break;  
    swap(*__i, *__j);  
}
```

# Branches in Quicksort

```
// Choose pivot  
// Partition the current range into two parts around the pivot  
while (true) {  
    while (__comp(*++__i, *__pivot));  
    while (!__comp(*--__j, *__pivot));  
    if (__i > __j) break;  
    swap(*__i, *__j);  
}
```

# Branches in Quicksort

```
// Choose pivot  
// Partition the current range into two parts around the pivot  
while (true) {  
    while (_comp(*++_i, *_pivot));  
    while (!_comp(*--_j, *_pivot));  
    if (_i > _j) break;  
    swap(*_i, *_j);  
}
```

- Outcome of comparison used for branching
- Data dependent branches are hard to predict
- [BlockQuickSort](#) reduces branches by separating the data movement from the comparison operation

# Reduce Branches: BlockQuickSort

```
uint64_t __left_bitset = 0;  
_RandomAccessIterator __iter = __first;  
for (int __j = 0; __j < __block_size;) {  
    bool __comp_result = !__comp(*__iter, __pivot);  
    __left_bitset |= (__comp_result << __j);  
    __j++;  
    ++__iter;  
}
```

# Reduce Branches: BlockQuickSort

```
uint64_t __left_bitset = 0;  
  
_RandomAccessIterator __i = __first;  
  
for (int __b = 0; __b < __block_size;) {  
    bool __comp_result = !__comp(*__i, __pivot);  
    __left_bitset |= (__comp_result << __b);  
    __b++;  
    ++__i;  
}
```

# Reduce Branches: BlockQuickSort

```
void __swap_bitset_pos(__first, __last, __left_bitset, __right_bitset) {
    while (__left_bitset != 0 && __right_bitset != 0) {
        difference_type tz_left = __ctz(__left_bitset);
        __left_bitset = __blsr(__left_bitset);
        difference_type tz_right = __ctz(__right_bitset);
        __right_bitset = __blsr(__right_bitset);
        _VSTD::iter_swap(__first + tz_left, __last - tz_right);
    }
}
```

# Reduce Branches: BlockQuickSort

```
void __swap_bitset_pos(__first, __last, __left_bitset, __right_bitset) {
    while (__left_bitset != 0 && __right_bitset != 0) {
        difference_type tz_left = __ctz(__left_bitset);
        __left_bitset = __blsr(__left_bitset);
        difference_type tz_right = __ctz(__right_bitset);
        __right_bitset = __blsr(__right_bitset);
        __VSTD::iter_swap(__first + tz_left, __last - tz_right);
    }
}
```

# Reduce Branches: BlockQuickSort

```
void __swap_bitset_pos(__first, __last, __left_bitset, __right_bitset) {
    while (__left_bitset != 0 && __right_bitset != 0) {
        difference_type tz_left = __ctz(__left_bitset);
        __left_bitset = __blsr(__left_bitset);
        difference_type tz_right = __ctz(__right_bitset);
        __right_bitset = __blsr(__right_bitset);
        _VSTD::iter_swap(__first + tz_left, __last - tz_right);
    }
}
```

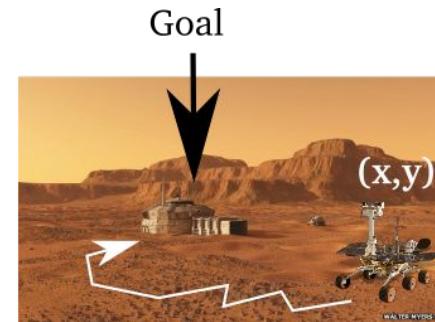
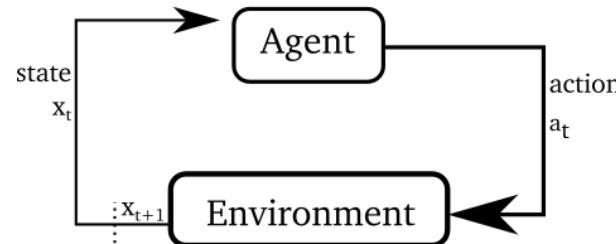
# Microbenchmark Results

Benchmark	Sorting time per element (ns)	
	Quicksort	BlockQuickSort
BM_Sort_uint32_Random_64	18.6	18.5
BM_Sort_uint32_Random_256	26.2	21.3
BM_Sort_uint32_Random_1024	33.4	23.3
BM_Sort_uint32_Random_16384	47.7	26.7
BM_Sort_uint32_Random_262144	62.6	30.1

# Small Sort Optimization with ML

# What is RL?

**Episode**  $(\text{state } s_0, \text{action } a_0, \text{next state } s_1, \text{next action } a_1, \dots)$



What do we want?

A **policy**  $\pi$ : what action  $a$  should I take in state  $s$ ?

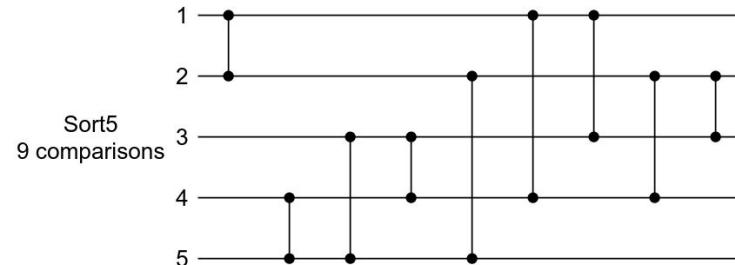
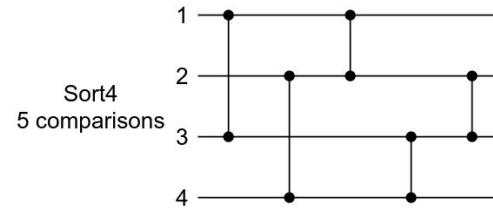
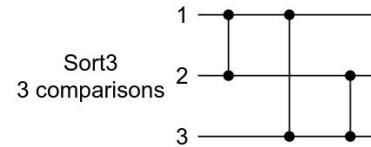
Deterministic:  $a = \pi(s)$

Stochastic:  $a \sim \pi(a|s)$

# Reinforcement Learning System

- Defined by a Markov Decision Process
  - States
    - Assembly program generated thus far
    - State of memory and registers
  - Actions
    - Assembly instructions - Intel AT&T syntax
  - Rewards
    - Correctness
    - Latency/program length
- Goal: Learn a policy that finds a correct, low latency program

# Sorting Networks\*



- <https://danlark.org/2022/04/20/changing-stdsort-at-googles-scale-and-beyond/>

# Conditional Swap

The image shows two side-by-side windows from the Compiler Explorer tool.

**Left Window (Compiler Explorer):**

- Title:** C++ source #1
- Language:** C++
- Code:**

```

1 #include <functional>
2
3 void cond_swap(int* __x, int* __y,
4                 std::less<int> __c) {
5     bool __r = __c(*__x, *__y);
6     int __tmp = __r ? *__x : *__y;
7     *__y = __r ? *__y : __tmp;
8     *__x = __tmp;
9 }
10

```

**Right Window (Compiler Explorer):**

- Title:** CppCast, the first podcast for C++ devs, by C++ devs
- Compiler:** x86-64 clang 14.0.0 (C++, Editor #1, Compiler #2)
- Flags:** -O3 -std=c++17 -stdlib=libc++
- Output:**

```

1 cond_swap(int*, int*, std::__1::less<int>):
2     movl (%rdi), %eax
3     movl (%rsi), %ecx
4     cmpl %ecx, %eax
5     movl %ecx, %edx
6     cmovl %eax, %edx
7     cmovl %ecx, %eax
8     movl %eax, (%rsi)
9     movl %edx, (%rdi)
10    retq

```

Annotations for the assembly code:

  - Line 2: `movl (%rdi), %eax` From pointers
  - Line 3: `movl (%rsi), %ecx` From pointers
  - Line 4: `cmpl %ecx, %eax` Compare
  - Line 5: `movl %ecx, %edx` Temporary
  - Line 6: `cmovl %eax, %edx` Swap if less
  - Line 7: `cmovl %ecx, %eax` Swap if less
  - Line 8: `movl %eax, (%rsi)` To pointers
  - Line 9: `movl %edx, (%rdi)` To pointers
  - Line 10: `retq`

# Sort3 with Condition Swap

The screenshot shows the Compiler Explorer interface with two panes. The left pane displays the C++ source code for a `__sort3_unstable_1` function, which implements the Sort3 algorithm with condition swap. The right pane shows the generated assembly code for x86-64 clang 14.0.0.

**C++ Source Code:**

```

48     __magic_swap(__x1, __x2, __x3, __c);
49 }
50
51 template <typename _Compare, typename _Random
52 inline void __sort3_unstable_1(_RandomAccessI
53     RandomAccessIterator __x3,
54     __cond_swap(__x2, __x3, __c);
55     __cond_swap(__x1, __x3, __c);
56     __cond_swap(__x1, __x2, __c);
57 }
58
59
60
61
62
63
64

```

**Assembly Output:**

```

1 Instantiator<unsigned long>::NotSoOptimized(unsigned long*):
2     movq    8(%rsi), %rax
3     movq    16(%rsi), %rcx
4     cmpq    %rcx, %rax
5     movq    %rcx, %rdx
6     cmovbq %rax, %rdx
7     movq    (%rsi), %rdi
8     cmovbq %rcx, %rax
9     cmpq    %rax, %rdi
10    movq   %rax, %rcx
11    cmovbq %rdi, %rcx
12    cmovaeq %rdi, %rax
13    movq   %rax, 16(%rsi)
14    cmpq    %rdx, %rcx
15    movq   %rdx, %rax
16    cmovbq %rcx, %rax
17    cmovbq %rdx, %rcx
18    movq   %rcx, 8(%rsi)
19    movq   %rax, (%rsi)
20    retq

```

The assembly code uses various memory operations (movq, cmovbq, cmovaeq) and comparisons (cmpq) between registers %rax, %rcx, and %rdx to implement the condition swap logic.

# Special Swap

```
1 // Ensures that *_x, *_y and *_z are ordered according to the comparator __c,
2 // under the assumption that *_y and *_z are already ordered.
3 template <class _Compare, class _RandomAccessIterator>
4 inline void __partially_sorted_swap(_RandomAccessIterator __x, _RandomAccessIterator __y,
5                                     _RandomAccessIterator __z, _Compare __c) {
6     using value_type = typename iterator_traits<_RandomAccessIterator>::value_type;
7     bool __r = __c(*__z, *__x);
8     value_type __tmp = __r ? *__z : *__x;
9     *__z = __r ? *__x : *__z;
10    __r = __c(__tmp, *__y);
11    *__x = __r ? *__x : *__y;
12 }
13
14 template <class _Compare, class _RandomAccessIterator>
15 inline void __sort3(_RandomAccessIterator __x1, _RandomAccessIterator __x2,
16                     _RandomAccessIterator __x3, _Compare __c) {
17     __VSTD::__cond_swap<_Compare>(__x2, __x3, __c);
18     __VSTD::__partially_sorted_swap<_Compare>(__x1, __x2, __x3, __c);
19 }
```

# Special Swap

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1 // Ensures that *_x, *_y and *_z are ordered according to the comparator __c,
2 // under the assumption that *_y and *_z are already ordered.
3 template <class _Compare, class _RandomAccessIterator>
4 inline void __partially_sorted_swap(_RandomAccessIterator __x, _RandomAccessIterator __y,
5                                     _RandomAccessIterator __z, _Compare __c) {
6     using value_type = typename iterator_traits<_RandomAccessIterator>::value_type;
7     bool __r = __c(*__z, *__x);
8     value_type __tmp = __r ? *__z : *__x;
9     *__z = __r ? *__x : *__z;
10    __r = __c(__tmp, *__y);
11    *__x = __r ? *__x : *__y;
12 }
13
14 template <class _Compare, class _RandomAccessIterator>
15 inline void __sort3(_RandomAccessIterator __x1, _RandomAccessIterator __x2,
16                     _RandomAccessIterator __x3, _Compare __c) {
17     __VSTD::__cond_swap<_Compare>(__x2, __x3, __c);
18     __VSTD::__partially_sorted_swap<_Compare>(__x1, __x2, __x3, __c);
19 }
```

# Special Swap

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1 // Ensures that *_x, *_y and *_z are ordered according to the comparator __c,
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9     *__z = __r ? *__x : *__z;
10    __r = __c(__tmp, *__y);
11    *__x = __r ? *__x : *__y;
12 }
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14 template <class _Compare, class _RandomAccessIterator>
15 inline void __sort3(_RandomAccessIterator __x1, _RandomAccessIterator __x2,
16                     _RandomAccessIterator __x3, _Compare __c) {
17     _VSTD::__cond_swap<_Compare>(__x2, __x3, __c);
18     _VSTD::__partially_sorted_swap<_Compare>(__x1, __x2, __x3, __c);
19 }
```

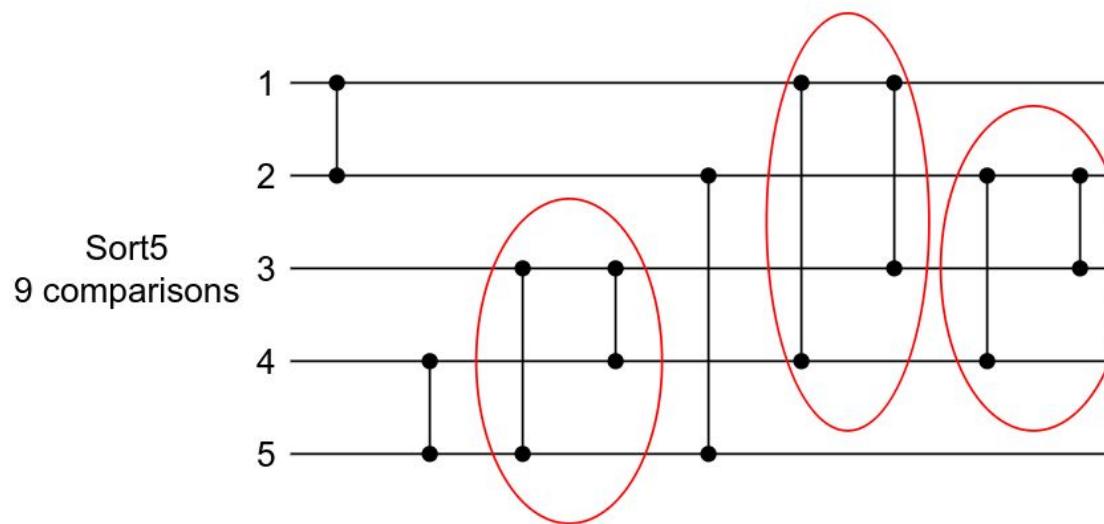
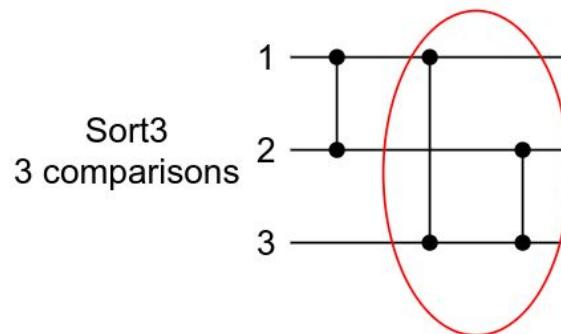
# Special Swap

Diff Viewer x86-64 clang 14.0.0 vs x86-64 clang 14.0.0				
A	Left: x86-64 clang (trunk) -O3 -s...	Assembly	Right: x86-64 clang (trunk) -O3 -s...	Assembly
1-Instantiator<unsigned long>::NotSoOptimized(unsigned long*)		1+Instantiator<unsigned long>::Optimized(unsigned long*):		
2	movq 8(%rsi), %rax		2	movq 8(%rsi), %rax
3	movq 16(%rsi), %rcx		3	movq 16(%rsi), %rcx
4	cmpq %rcx, %rax		4	cmpq %rcx, %rax
5	movq %rcx, %rdx		5	movq %rcx, %rdx
6	cmoveq %rax, %rdx		6	cmoveq %rax, %rdx
7	movq (%rsi), %rdi		7	movq (%rsi), %rdi
8	cmoveq %rcx, %rax		8	cmoveq %rcx, %rax
9-	cmpq %rax, %rdi		9+	cmpq %rdi, %rax
10-	movq %rax, %rcx		10+	movq %rdi, %rcx
11-	cmoveq %rdi, %rcx		11+	cmoveq %rax, %rcx
12-	cmoveq %rdi, %rax		12+	cmoveq %rdi, %rax
13	movq %rax, 16(%rsi)		13	movq %rax, 16(%rsi)
14	cmpq %rdx, %rcx		14	cmpq %rdx, %rcx
15-	movq %rdx, %rax		15+	cmoveq %rdx, %rdi
16-	cmoveq %rcx, %rax		16+	movq %rdi, (%rsi)
17	cmoveq %rdx, %rcx		17	cmoveq %rdx, %rcx
18	movq %rcx, 8(%rsi)		18	movq %rcx, 8(%rsi)
19-	movq %rax, (%rsi)		19	retq
20	retq			

# Special Swap

Diff Viewer x86-64 clang 14.0.0 vs x86-64 clang 14.0.0				
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1-Instantiator<unsigned long>::NotSoOptimized(unsigned long*)		1+Instantiator<unsigned long>::Optimized(unsigned long*):		
2	movq 8(%rsi), %rax		2	movq 8(%rsi), %rax
3	movq 16(%rsi), %rcx		3	movq 16(%rsi), %rcx
4	cmpq %rcx, %rax		4	cmpq %rcx, %rax
5	movq %rcx, %rdx		5	movq %rcx, %rdx
6	cmoveq %rax, %rdx		6	cmoveq %rax, %rdx
7	movq (%rsi), %rdi		7	movq (%rsi), %rdi
8	cmoveq %rcx, %rax		8	cmoveq %rcx, %rax
9-	cmpq %rax, %rdi		9+	cmpq %rdi, %rax
10-	movq %rax, %rcx		10+	movq %rdi, %rcx
11-	cmoveq %rdi, %rcx		11+	cmoveq %rax, %rcx
12-	cmoveq %rdi, %rax		12+	cmoveq %rdi, %rax
13	movq %rax, 16(%rsi)		13	movq %rax, 16(%rsi)
14	cmpq %rdx, %rcx		14	cmpq %rdx, %rcx
15-	movq %rdx, %rax		15+	cmoveq %rdx, %rdi
16-	cmoveq %rcx, %rax		16+	movq %rdi, (%rsi)
17	cmoveq %rdx, %rcx		17	cmoveq %rdx, %rcx
18	movq %rcx, 8(%rsi)		18	movq %rcx, 8(%rsi)
19-	movq %rax, (%rsi)		19	retq
20	retq			

# Multiple Special Swaps



# Micro-benchmarks

## ARMv8

name	old cpu/op	new cpu/op	delta	
BM_Sort_uint32_Random_1	3.85ns ± 0%	4.01ns ± 0%	+3.95%	(p=0.000 n=99+63)
BM_Sort_uint32_Random_4	4.83ns ± 0%	2.05ns ± 0%	-57.50%	(p=0.000 n=97+94)
BM_Sort_uint32_Random_16	9.59ns ± 0%	9.15ns ± 0%	-4.59%	(p=0.000 n=98+95)
BM_Sort_uint32_Random_64	16.2ns ± 0%	15.7ns ± 0%	-2.99%	(p=0.000 n=94+99)
BM_Sort_uint32_Random_256	22.3ns ± 1%	21.7ns ± 0%	-2.77%	(p=0.000 n=100+100)
BM_Sort_uint32_Random_1024	28.5ns ± 0%	27.7ns ± 0%	-2.64%	(p=0.000 n=99+100)
BM_Sort_uint32_Random_16384	40.3ns ± 1%	39.4ns ± 1%	-2.17%	(p=0.000 n=98+100)
BM_Sort_uint32_Random_262144	51.8ns ± 2%	50.9ns ± 2%	-1.69%	(p=0.000 n=100+100)
BM_Sort_uint64_Random_1	4.02ns ± 0%	3.93ns ± 2%	-2.32%	(p=0.000 n=96+95)
BM_Sort_uint64_Random_4	5.03ns ± 0%	2.18ns ± 0%	-56.68%	(p=0.000 n=95+96)
BM_Sort_uint64_Random_16	9.63ns ± 0%	9.22ns ± 0%	-4.32%	(p=0.000 n=98+98)
BM_Sort_uint64_Random_64	16.2ns ± 0%	15.9ns ± 0%	-2.18%	(p=0.000 n=100+99)
BM_Sort_uint64_Random_256	22.4ns ± 0%	22.1ns ± 0%	-1.49%	(p=0.000 n=98+98)
BM_Sort_uint64_Random_1024	28.4ns ± 0%	28.0ns ± 0%	-1.16%	(p=0.000 n=98+100)
BM_Sort_uint64_Random_16384	40.0ns ± 1%	39.7ns ± 1%	-0.81%	(p=0.000 n=96+99)
BM_Sort_uint64_Random_262144	51.6ns ± 2%	51.4ns ± 2%	-0.48%	(p=0.000 n=98+99)

# Micro-benchmarks

## ARMv8

name	old cpu/op	new cpu/op	delta	
BM_Sort_uint32_Random_1	3.85ns ± 0%	4.01ns ± 0%	+3.95%	(p=0.000 n=99+63)
BM_Sort_uint32_Random_4	4.83ns ± 0%	2.05ns ± 0%	-57.50%	(p=0.000 n=97+94)
BM_Sort_uint32_Random_16	9.59ns ± 0%	9.15ns ± 0%	-4.59%	(p=0.000 n=98+95)
BM_Sort_uint32_Random_64	16.2ns ± 0%	15.7ns ± 0%	-2.99%	(p=0.000 n=94+99)
BM_Sort_uint32_Random_256	22.3ns ± 1%	21.7ns ± 0%	-2.77%	(p=0.000 n=100+100)
BM_Sort_uint32_Random_1024	28.5ns ± 0%	27.7ns ± 0%	-2.64%	(p=0.000 n=99+100)
BM_Sort_uint32_Random_16384	40.3ns ± 1%	39.4ns ± 1%	-2.17%	(p=0.000 n=98+100)
BM_Sort_uint32_Random_262144	51.8ns ± 2%	50.9ns ± 2%	-1.69%	(p=0.000 n=100+100)
BM_Sort_uint64_Random_1	4.02ns ± 0%	3.93ns ± 2%	-2.32%	(p=0.000 n=96+95)
BM_Sort_uint64_Random_4	5.03ns ± 0%	2.18ns ± 0%	-56.68%	(p=0.000 n=95+96)
BM_Sort_uint64_Random_16	9.63ns ± 0%	9.22ns ± 0%	-4.32%	(p=0.000 n=98+98)
BM_Sort_uint64_Random_64	16.2ns ± 0%	15.9ns ± 0%	-2.18%	(p=0.000 n=100+99)
BM_Sort_uint64_Random_256	22.4ns ± 0%	22.1ns ± 0%	-1.49%	(p=0.000 n=98+98)
BM_Sort_uint64_Random_1024	28.4ns ± 0%	28.0ns ± 0%	-1.16%	(p=0.000 n=98+100)
BM_Sort_uint64_Random_16384	40.0ns ± 1%	39.7ns ± 1%	-0.81%	(p=0.000 n=96+99)
BM_Sort_uint64_Random_262144	51.6ns ± 2%	51.4ns ± 2%	-0.48%	(p=0.000 n=98+99)

# Thank You

# References

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