
Vultur gryphus, Hugo Pédel
CC BY-SA 3.0
Glide.

Glidesort

Efficient In-Memory Adaptive Stable Sorting on Modern Hardware

Orson Peters
Research done at CWI Database Architectures group

What is glidesort?

- General purpose **stable comparison sort.**
- A hybrid of mergesort, quicksort and block insertion sort.
- **Robustly** adaptive to pre-sorted and low-cardinality inputs.
- Reference implementation in (unsafe) Rust.

Drop-in for `[T]::sort`

Stable quicksort?

Yes!

https://github.com/scandum/fluxsort

Igor van den Hoven

Quicksort

From Wikipedia, the free encyclopedia

Quicksort is an in-place sorting algorithm. Developed by British computer scientist Tony Hoare in 1959[1] and published in 1961,[2] it is still a commonly used algorithm for sorting. When implemented well, it can be somewhat faster than merge sort and about two or three times faster than heapsort.[3][*contradictory*]

Quicksort is a divide-and-conquer algorithm. It works by selecting a 'pivot' element from the array and partitioning the other elements into two sub-arrays, according to whether they are less than or greater than the pivot. For this reason, it is sometimes called **partition-exchange sort**.[4] The sub-arrays are then sorted recursively. This can be done in-place, requiring small additional amounts of memory to perform the sorting.

Quicksort is a comparison sort, meaning that it can sort items of any type for which a "less-than" relation (formally, a total order) is defined. Efficient implementations of Quicksort are not a stable sort, meaning that the relative order of equal sort items is not preserved.

std::stable_sort uses O(n) auxiliary memory and no one bats an eye

Stable quicksort uses O(n) auxiliary memory and everyone loses their minds

Adaptive sorting

adapt verb

To change your behaviour in order to deal more successfully with a new situation.

Divide and conquer

Merge

- Mergesort
- Timsort
- Powersort

Partition

- Quicksort
- Samplesort
- Radix sort

Fundamentally **bottom-up.**
Can be *adaptive* to pre-sorted runs.

Fundamentally **top-down**.
Can be *adaptive* to low-cardinality inputs.

Low-cardinality inputs

```
SELECT * FROM customers ORDER BY city;

SELECT * FROM cars ORDER BY brand;
```

Adaptive quicksort

Idea:

- During partitioning detect buckets of all-equal elements.

Challenges:

- Minimize overhead comparisons.
- Avoiding three-way comparisons.

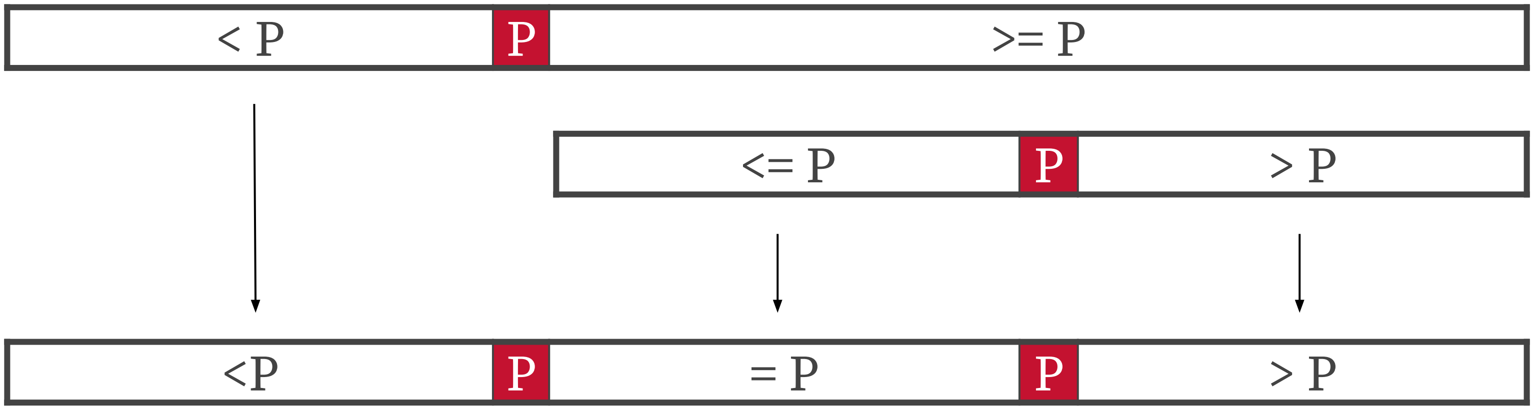
Rough history:

- Quicksort (Hoare, 1961)
- Dutch national flag problem (Dijkstra, 1976)
- Unix qsort (Bentley-McIlroy, 1992)
- Pattern-defeating quicksort (Orson Peters, 2015)

Adaptive pdqsort

See earlier talk on pdqsort: https://www.youtube.com/watch?v=jz-PBiWwNjc

Adaptive pdqsort



Each value can be a pivot at most twice:

On average O(n log(k)) for k distinct values

Adaptive mergesort

Idea:

- Merge pre-existing runs.

Challenges:

- Minimize unbalanced merges.
- Storing run information.

Rough history:

- Mergesort (von Neumann, 1945)
- Natural mergesort (Knuth, 1973)
- Timsort (*Tim* Peters, 2002)
- Powersort (Munro-Wild, 2018)

Powersort

Nearly-Optimal Mergesorts: Fast, Practical Sorting Methods That Optimally Adapt to Existing Runs
J. Ian Munro, Sebastian Wild

Outline of main loop:

```
1.   run = create_run(prev_run.end, array)
2.   p = power(prev_run, run)
3.   while peek(stack).p > p:
          run = merge(pop(stack).run, run)
4.   push(stack, (run, p))
5.   prev_run = run
```

- Stack is at most $\log_2(n)$ runs.
- Provably creates good and stable merge sequences heuristically.
- `create_run` can take advantage of existing runs in input.

A problem emerges

Merge

- Mergesort
- Timsort
- Powersort

Partition

- Quicksort
- Samplesort
- Radix sort

Fundamentally **bottom-up.**

Can be *adaptive* to pre-sorted runs.

Fundamentally **top-down**.

Can be *adaptive* to low-cardinality inputs.


Vultur gryphus, Hugo Pédel
CC BY-SA 3.0
Glide.

```rust
enum Run {
    Unsorted(Range),
    Sorted(Range),
    Concatenated((Range, Range)),
}
```

A soaring bird only flaps its wings when necessary.

Powersort

Nearly-Optimal Mergesorts: Fast, Practical Sorting Methods That Optimally Adapt to Existing Runs
J. Ian Munro, Sebastian Wild

Outline of main loop:

```
1.  run = create_run(prev_run.end, array)
2.  p = power(prev_run, run)
3.  while peek(stack).p > p:
        run = merge(pop(stack).run, run)
4.  push(stack, (run, p))
5.  prev_run = run
```

- Stack is at most $\log_2(n)$ runs.
- Provably creates good and stable merge sequences.
- `create_run` can take advantage of existing runs in input.

Creating a ‘run’

```
create_run(start, array)
```

1. Scan array while nondecreasing (or strictly descending) to find `run`.
2. If bigger than `RUN_THRESHOLD`, (reverse) and return `Run::Sorted(run)`.
3. Otherwise, return a `Run::Unsorted` with length `RUN_THRESHOLD`.

‘Merging’ two ‘runs’

```
fn logical_merge(left_run: Run, right_run: Run) -> Run {
    match (left_run, right_run) {
        (Unsorted(l), Unsorted(r)) => {
            if l.len() + r.len() <= scratch_space.len() {
                Unsorted(Range(l.begin, r.end))
            } else {
                Concatenated(quicksort(l), quicksort(r))
            }
        },
        (      Sorted(l), Sorted(r))       => Concatenated((l, r)),
        (    Unsorted(l), right_run)       => logical_merge(quicksort(l), right_run),
        (       left_run, Unsorted(r))     => logical_merge(left_run, quicksort(r)),
        (Concatenated(l), Sorted(r))       => physical_triple_merge(l.0, l.1, r),
        (      Sorted(l), Concatenated(r)) => physical_triple_merge(l, r.0, r.1),
        (Concatenated(l), Concatenated(r)) => physical_quad_merge(l.0, l.1, r.0, r.1),
    }
}
```

‘Merging’ two ‘runs’

```
fn logical_merge(left_run: Run, right_run: Run) -> Run {
    match (left_run, right_run) {
        (Unsorted(l), Unsorted(r)) => {
            if l.len() + r.len() <= scratch_space.len() {
                Unsorted(Range(l.begin, r.end))
            } else {
                Concatenated(quicksort(l), quicksort(r))
            }
        },
        (      Sorted(l), Sorted(r))       => Concatenated((l, r)),
        (    Unsorted(l), right_run)       => logical_merge(quicksort(l), right_run),
        (       left_run, Unsorted(r))     => logical_merge(left_run, quicksort(r)),
        (Concatenated(l), Sorted(r))       => physical_triple_merge(l.0, l.1, r),
        (      Sorted(l), Concatenated(r)) => physical_triple_merge(l, r.0, r.1),
        (Concatenated(l), Concatenated(r)) => physical_quad_merge(l.0, l.1, r.0, r.1),
    }
}
```

‘Merging’ two ‘runs’

```
fn logical_merge(left_run: Run, right_run: Run) -> Run {
    match (left_run, right_run) {
        (Unsorted(l), Unsorted(r)) => {
            if l.len() + r.len() <= scratch_space.len() {
                Unsorted(Range(l.begin, r.end))
            } else {
                Concatenated(quicksort(l), quicksort(r))
            }
        },
        (      Sorted(l), Sorted(r))       => Concatenated((l, r)),
        (    Unsorted(l), right_run)       => logical_merge(quicksort(l), right_run),
        (       left_run, Unsorted(r))     => logical_merge(left_run, quicksort(r)),
        (Concatenated(l), Sorted(r))       => physical_triple_merge(l.0, l.1, r),
        (      Sorted(l), Concatenated(r)) => physical_triple_merge(l, r.0, r.1),
        (Concatenated(l), Concatenated(r)) => physical_quad_merge(l.0, l.1, r.0, r.1),
    }
}
```

‘Merging’ two ‘runs’

```
fn logical_merge(left_run: Run, right_run: Run) -> Run {
    match (left_run, right_run) {
        (Unsorted(l), Unsorted(r)) => {
            if l.len() + r.len() <= scratch_space.len() {
                Unsorted(Range(l.begin, r.end))
            } else {
                Concatenated(quicksort(l), quicksort(r))
            }
        },
        (      Sorted(l), Sorted(r))       => Concatenated((l, r)),
        (    Unsorted(l), right_run)       => logical_merge(quicksort(l), right_run),
        (       left_run, Unsorted(r))     => logical_merge(left_run, quicksort(r)),
        (Concatenated(l), Sorted(r))       => physical_triple_merge(l.0, l.1, r),
        (      Sorted(l), Concatenated(r)) => physical_triple_merge(l, r.0, r.1),
        (Concatenated(l), Concatenated(r)) => physical_quad_merge(l.0, l.1, r.0, r.1),
    }
}
```

‘Merging’ two ‘runs’

```
fn logical_merge(left_run: Run, right_run: Run) -> Run {
    match (left_run, right_run) {
        (Unsorted(l), Unsorted(r)) => {
            if l.len() + r.len() <= scratch_space.len() {
                Unsorted(Range(l.begin, r.end))
            } else {
                Concatenated(quicksort(l), quicksort(r))
            }
        },
        (       Sorted(l), Sorted(r))       => Concatenated((l, r)),
        (     Unsorted(l), right_run)       => logical_merge(quicksort(l), right_run),
        (        left_run, Unsorted(r))     => logical_merge(left_run, quicksort(r)),
        (Concatenated(l), Sorted(r))        => physical_triple_merge(l.0, l.1, r),
        (       Sorted(l), Concatenated(r)) => physical_triple_merge(l, r.0, r.1),
        (Concatenated(l), Concatenated(r))  => physical_quad_merge(l.0, l.1, r.0, r.1),
    }
}
```

Glidesort main loop summary

- Extension of powersort (but applicable to any natural stable mergesort)
- Does not eagerly sort small runs
- Defers physically merging as long as possible
- Transforms sorting problem into quicksorts and triple/quad merges
- Adaptive to pre-sorted runs and low-cardinality inputs

Why triple/quad merges?

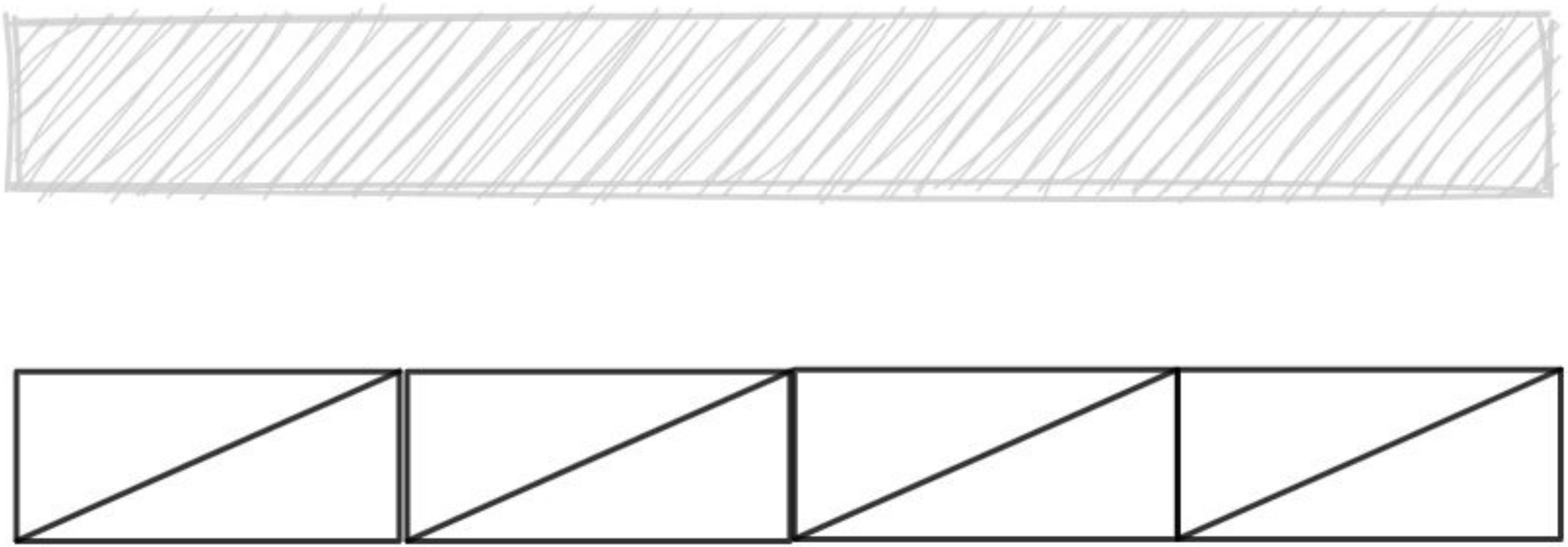
1. Ping-pong merging
2. Bidirectional merging
3. Parallel merging

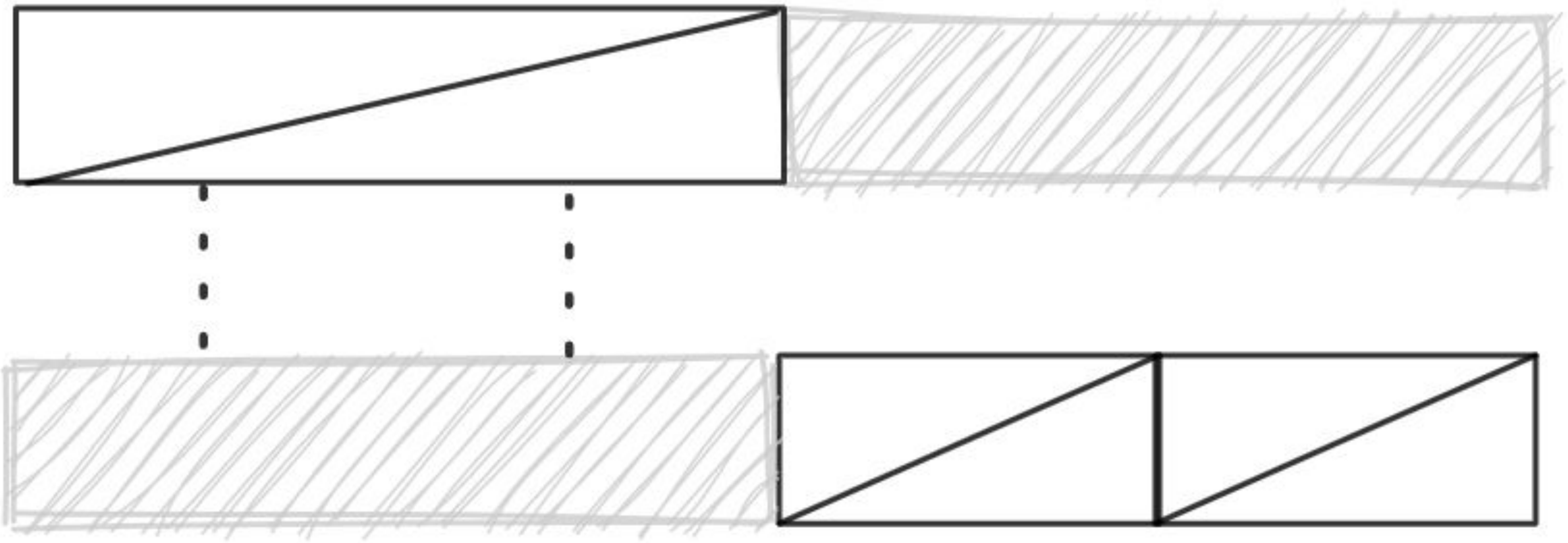
Ping-pong merges

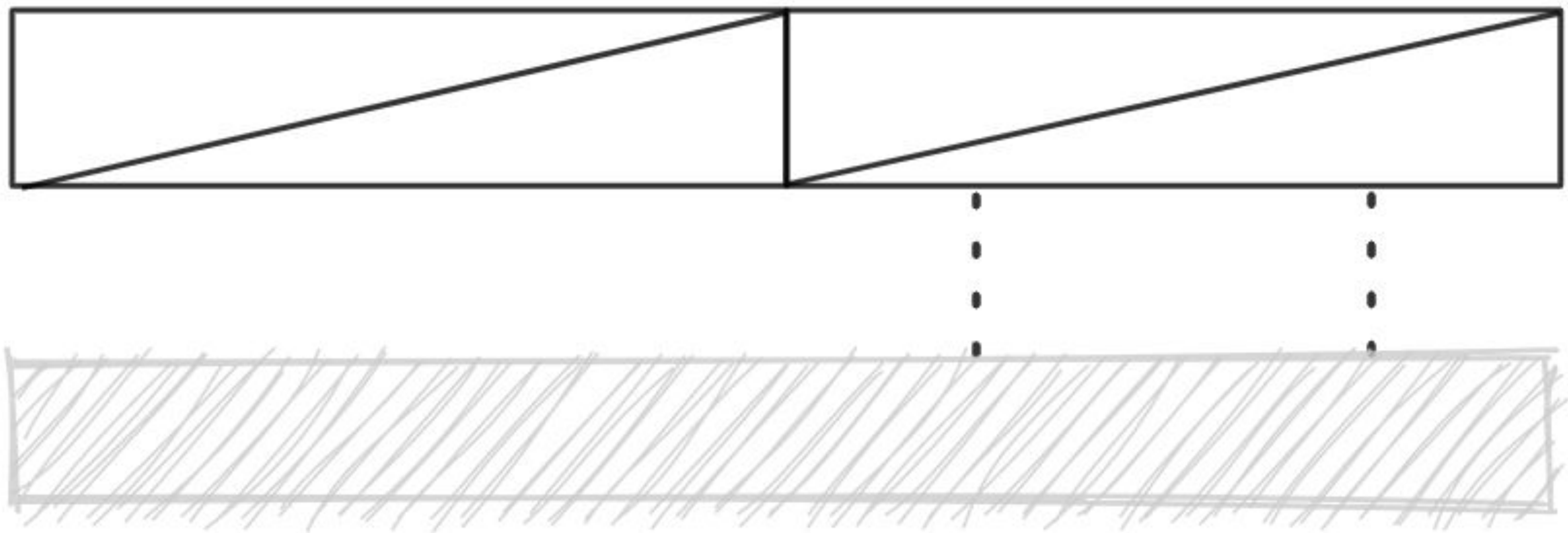
Patience is a Virtue: Revisiting Merge and Sort on Modern Processors
Badrish Chandramouli, Jonathan Goldstein

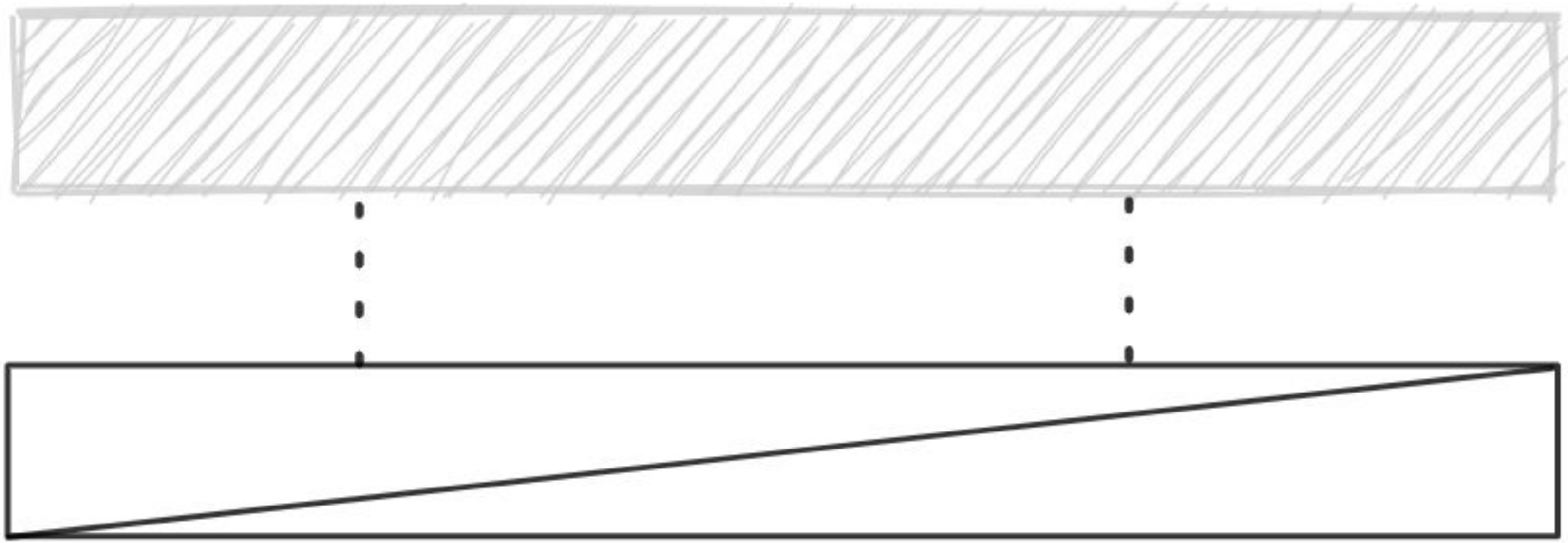
https://github.com/scandum/quadsort
Igor van den Hoven

- Traditional merge memcpy’s smaller array to scratch space before merging back
- Triple/quad merges can merge both *into* the scratch space and back









Bidirectional merging

- Destination and source arrays disjoint?
- Merge from both ends!

```
loop {
    let common = self.left.len().min(self.right.len());
    if common == 0 { break; }
    for _ in 0..common / 4 {
        self.branchless_merge_one_at_begin(is_less);
        self.branchless_merge_one_at_end(is_less);
        self.branchless_merge_one_at_begin(is_less);
        self.branchless_merge_one_at_end(is_less);
    }
    for _ in 0..common % 4 {
        self.branchless_merge_one_at_begin(is_less);
    }
}
```

'Parity merge'
https://github.com/scandum/quadsort
Igor van den Hoven

Modern processors are:

1. superscalar
2. out-of-order
3. deeply pipelined

Branchless merge (at begin)

Branch Mispredictions Don't Affect Mergesort
Amr Elmasry, Jyrki Katajainen & Max Stenmark

```
let left_scan = self.left.begin();
let right_scan = self.right.begin();
let right_less = is_less(&*right_scan, &*left_scan);
let src = select(right_less, right_scan, left_scan);
ptr::copy_nonoverlapping(src, self.out.begin(), 1);
self.out.add_begin(1);
self.right.add_begin(right_less as usize);
self.left.add_begin((!right_less) as usize);
```

Dependencies

```
let left_scan = self.left.begin();
let right_scan = self.right.begin();
let right_less = is_less(&*right_scan, &*left_scan);
let src = select(right_less, right_scan, left_scan);
ptr::copy_nonoverlapping(src, self.out.begin(), 1);
self.out.add_begin(1);
self.right.add_begin(right_less as usize);
self.left.add_begin((!right_less) as usize);
```

Interleave independent branchless loops.

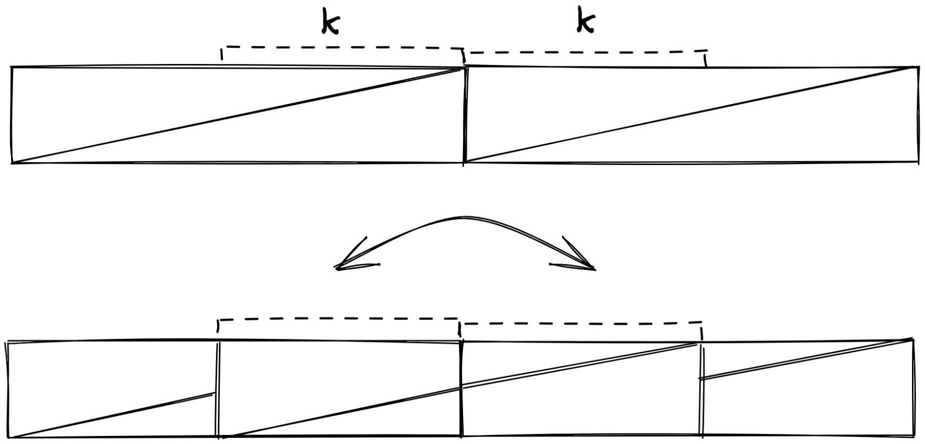
(within reason - don't spill to stack / overload prefetcher)

‘Parallel’ merging

- First step in quad merge has two independent merges
- Can parallelize, but no threads…
- …interleave loops

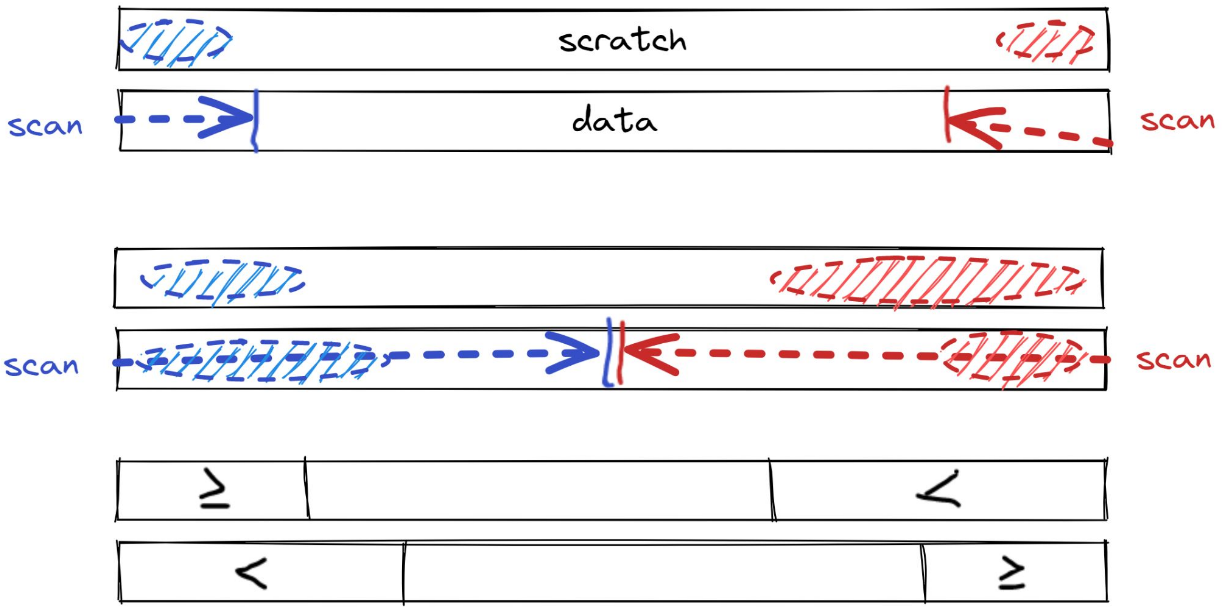
Creating more parallelism

- With binary search we can find crossover point
  `L[len(L)-k] > R[k]`
- Swap last/first k elements
- Out-of-place merge? Swap is free!
- O(n log(n)^2) fallback for stable merging with O(1) buffer



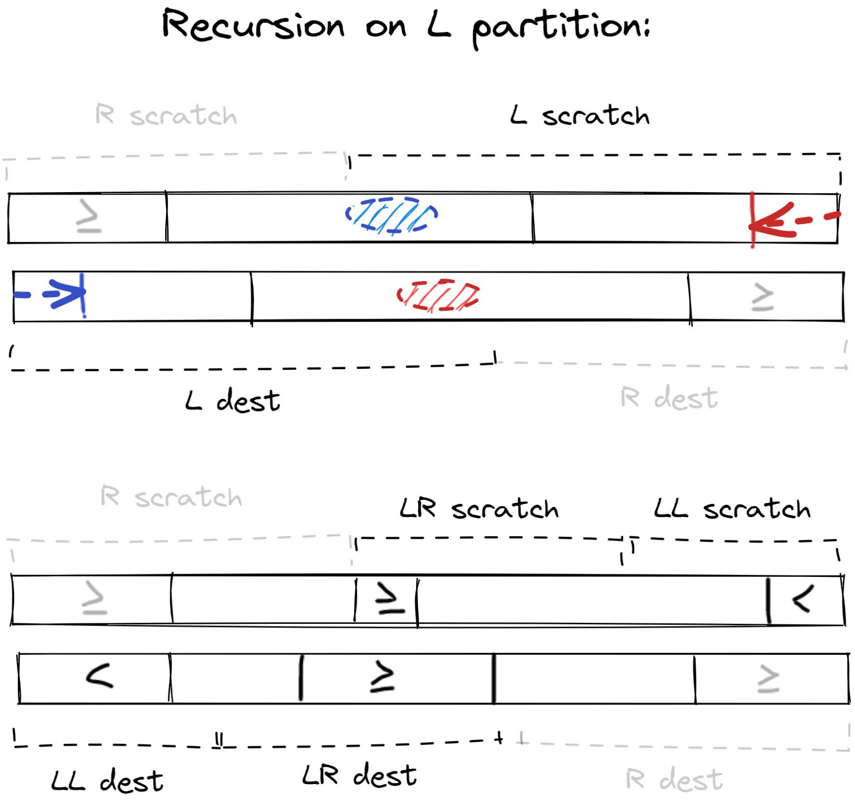
Bidirectional stable partitioning

Same principle, interleaving two independent scans



Bidirectional stable partitioning

- Recursion is a bit more involved…
- Input partially in scratch, partially in destination
- Invariant |dest| = |scratch| = |L| + |R|



Experimental setup

Your mileage ~~may~~ will vary

macOS Monterey 12.1

Rust nightly, release profile
`Link-time optimization = "thin"`

Clang 13.0
`g++ -std=c++17 -O2`

2021 Apple M1 Pro high perf. core
Max frequency: 3.2GHz
L1: 128 KiB (data), 196 KiB (instr)
L2: 12 MiB (shared)
L3: n/a

All figures reported are *medians*, all experiments single-threaded.

ns/N $\log_2$ N		N = 2^{24} (5x cache)		32-bit integers		a < b	
	Stable	Buffer	Shuffled	Half-sorted	Append 1%	Ascending	Descending
glidesort	**Yes**	n/2	**0.624**	**0.338**	0.077	**0.014**	**0.017**
glidesort1024	**Yes**	**1024**	1.373	0.723	0.123	**0.014**	**0.017**
Rust stable	**Yes**	n/2	2.710	1.425	0.120	0.016	0.026
std::stable_sort	**Yes**	n/2	3.012	1.689	0.276	0.252	0.780
cpp-timsort	**Yes**	n/2	3.579	1.876	**0.069**	0.024	0.029
pdqsort	No	**O(1)**	0.912	0.918	0.732	0.036	0.058
Rust unstable	No	**O(1)**	1.136	1.119	1.044	0.016	0.019
std::sort	No	**O(1)**	2.629	2.222	0.601	0.039	0.072

~4.3x faster than Rust stable sort

~4.7x faster than std::stable_sort

for random data

Apple M1 Macbook Pro

Stable sort observable, cardinality 256

ns/N $\log_2$ N		$N = 2^{24}$ (5x cache)		32-bit integers		a % 256 < b % 256	
	Stable	Buffer	Shuffled	Half-sorted	Append 1%	Ascending	Descending
glidesort	**Yes**	n/2	**0.261**	**0.151**	0.083	**0.018**	0.167
glidesort1024	**Yes**	**1024**	1.212	0.630	0.046	**0.018**	0.043
Rust stable	**Yes**	n/2	3.334	1.759	0.154	0.021	0.621
std::stable_sort	**Yes**	n/2	1.714	1.009	0.305	0.292	0.287
cpp-timsort	**Yes**	n/2	2.102	1.074	**0.053**	0.024	0.079
pdqsort	No	**O(1)**	1.043	0.729	0.163	0.041	0.090
Rust unstable	No	**O(1)**	0.348	0.315	0.487	0.020	0.130
std::sort	No	**O(1)**	1.048	0.765	0.181	0.039	0.078

~12.8x faster than Rust stable sort

~6.6x faster than std::stable_sort

for random data

Apple M1 Macbook Pro

Released now!

github.com/orlp/glidesort

```
cargo add glidesort
```

Y Hacker News new | threads | past | comments | ask | show | jobs | submit

1. * Show HN: Glidesort, a new stable sort in Rust up to ~4x faster for random data (github.com/orlp)
119 points by orlp 1 hour ago | hide | 13 comments | edit

435 Glidesort, a new stable sort in Rust up to ~4x faster for random data (github.com)
submitted 13 hours ago by nightcracker
35 comments share save hide delete nsfw spoiler crosspost

Rust specifics

Unwinding panics are Rust's billion dollar mistake


throw
catch
panic!
catch_unwind
Corporate needs you to find the differences between this picture and this picture.
They're the same picture.

Unwinding panics & generic unsafe code

1. Foreign code? **Any** call can cause unwinding.
2. Safe function? Have to be sound even during unwinding.
3. **All traits are foreign code.**

Unwinding panics & generic unsafe code

Writing non-trivial generic unsafe code is a nightmare.

All algorithm state in structs with Drop handlers.

~10-15% performance penalty in Glidesort *for integers* (can’t even panic!)

A great strength

- Moves are `memcpy`s, no move constructor!
- Makes optimizations possible:

```
// ptr::copy(scan, if less { dest } else { scratch }, 1);
ptr::copy(scan, dest, 1);
ptr::copy(scan, scratch, 1);
```

- Opposite of unwinding panics: no surprises.

Safe concatenation

- `[T]::split_at_mut` is a one-way street
- Glidesort needs concatenation…
- Raw pointers?
- Branded slices!

GhostCell: Separating Permissions from Data in Rust

Joshua Yanovski, Hoang-Hai Dang, Ralf Jung, Derek Dreyer.

```rust
pub struct MutSlice<'l, B, T, S> {
    begin: *mut T,
    end: *mut T,
    _lifetime: PhantomData<&'l mut T>,
    _metadata: PhantomData<(B, S)>,
}
```

Brand

State

All slices within Glidesort are `MutSlice`s!

unsafe `upgrade()`

`assume_uninit()`

unsafe `assume_init()`

unsafe `take()`

Example transitions

Weak ↔ `(*mut T, *mut T)`

Uninit, MaybeInit, Init → `&mut [MaybeUninit<T>]`

AlwaysInit ↔ `&mut [T]`

I’m leaving academia

I’m open to interesting* (Rust) jobs!

https://orlp.net

https://linkedin.com/in/orson-peters

*I am not interested in cryptocurrency, Web3 or similar ventures.

Vultur gryphus, Hugo Pédel