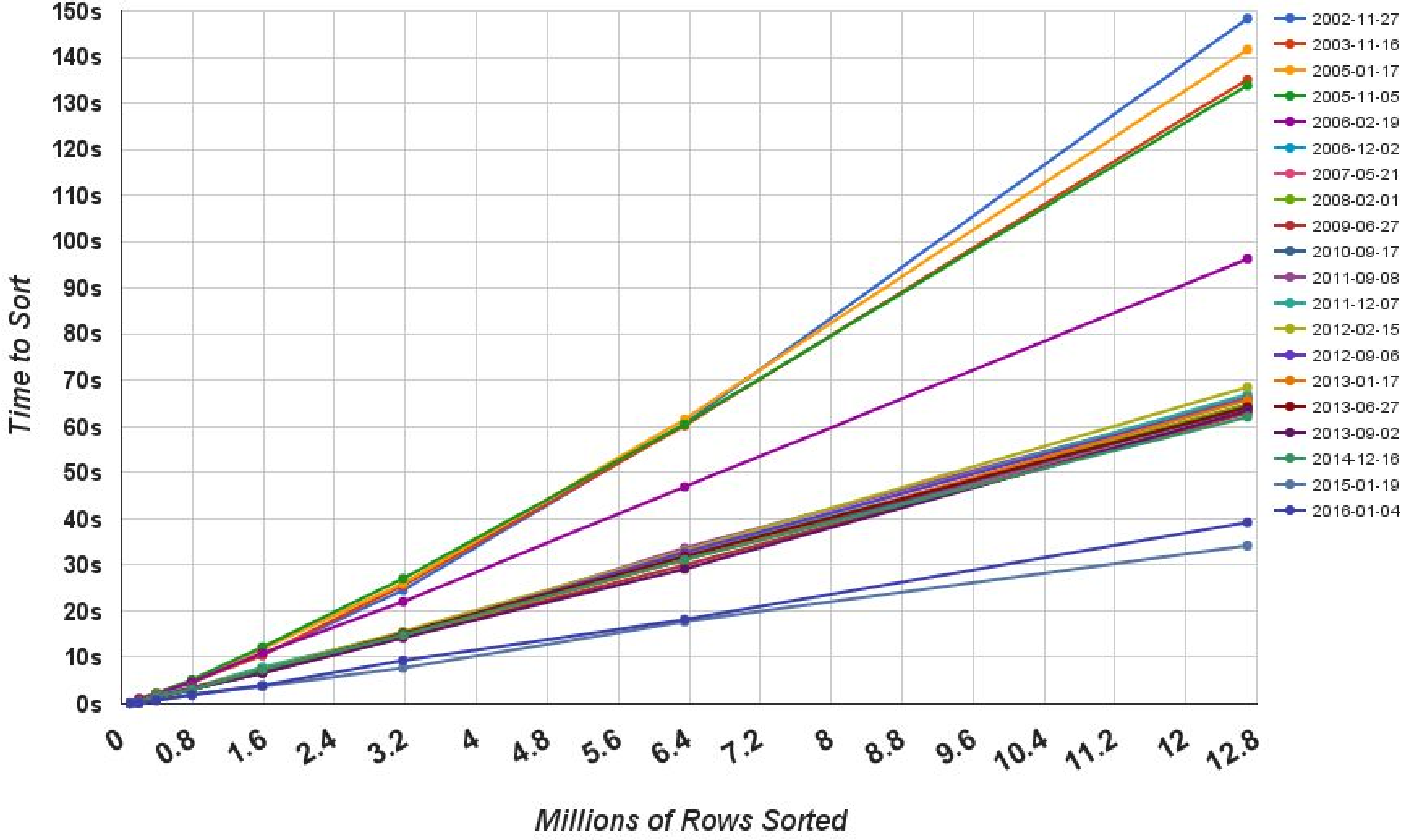
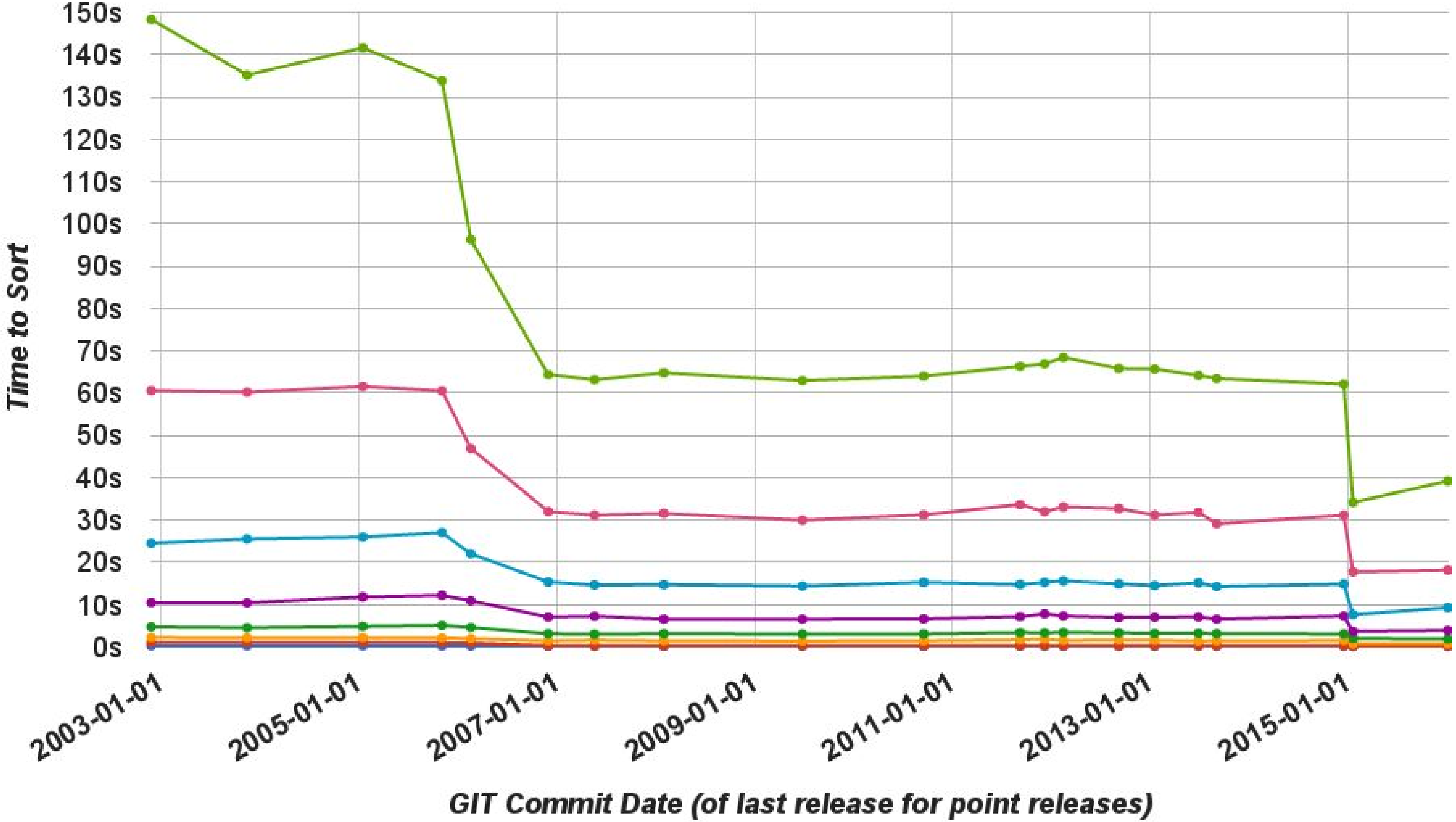
Sorting Through The Ages

- Why sorting?
  - It's a nice isolated module that's easy to understand without understanding the entire PostgreSQL code base
  - It's highly visible for users and affects many queries and commands
- But why the history?
  - Understanding the decisions that led to the current code helps explain why things are the way they are today and what factors led to the limitations and compromises that are there today
  - Many of the changes fixed real problems that users faced, and understanding past problems shows us what future problems and their solutions may look like

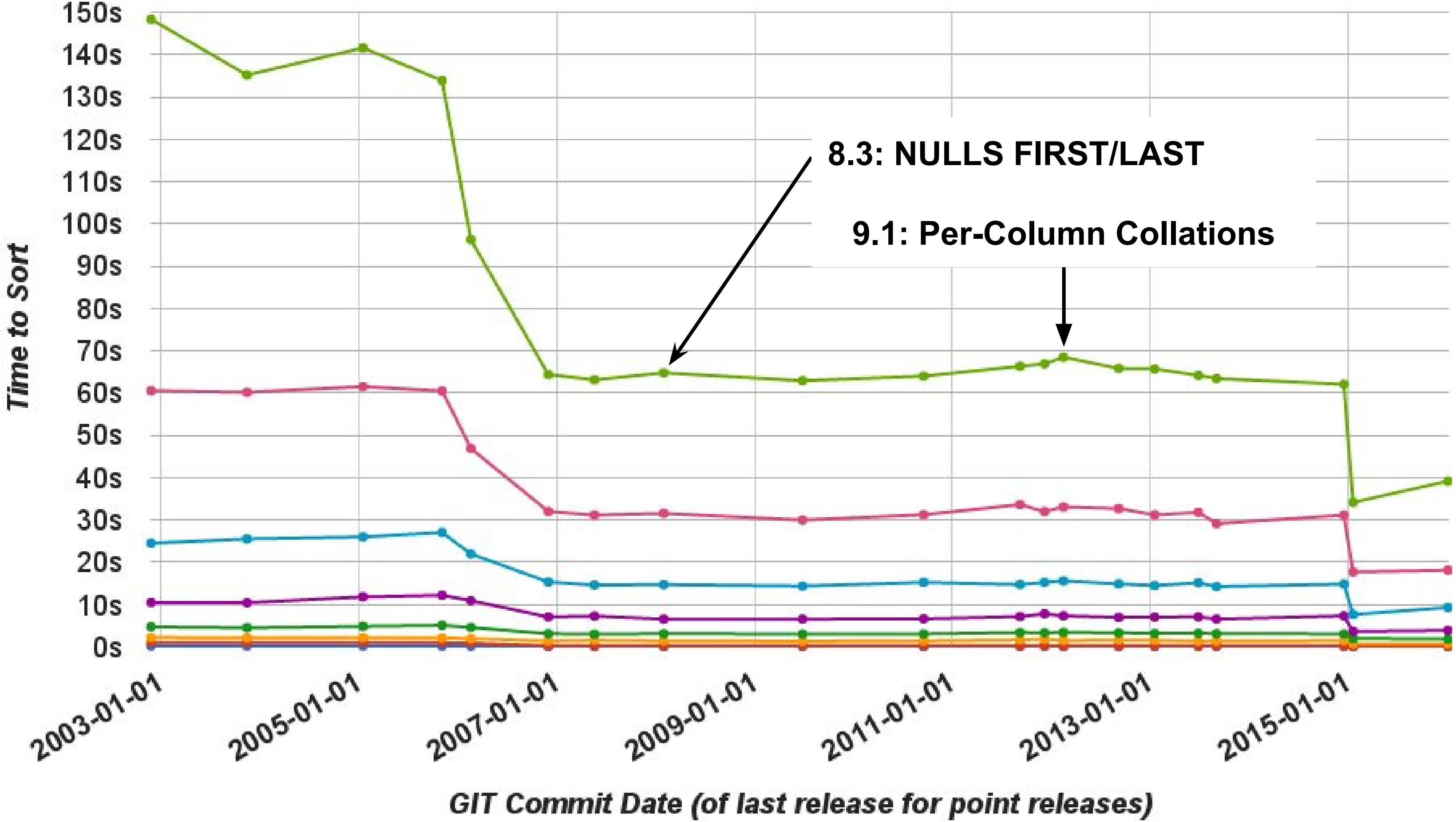
Sorting Through The Ages



Sorting Through The Ages



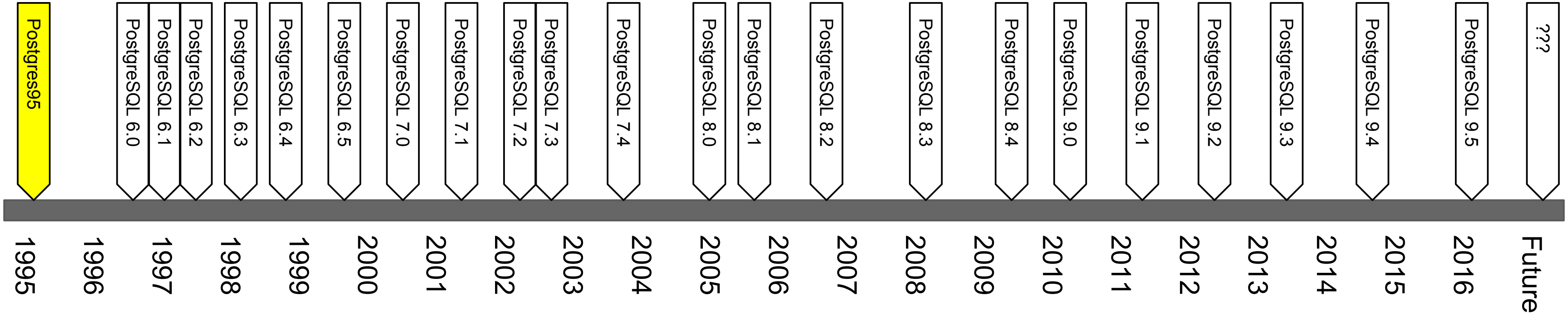
Sorting Through The Ages



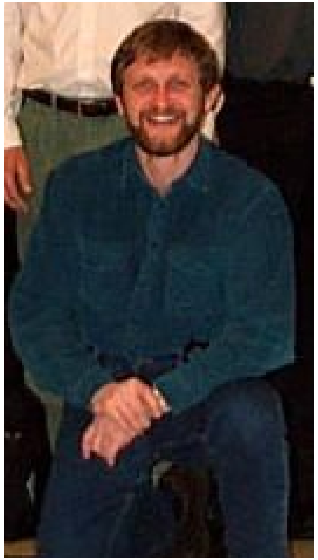
Postgres95 - First public release

Sort code in psort.c is 618 lines long.

It implements only one sort algorithm, an external (on-disk) algorithm out of Knuth called Replacement Selection.

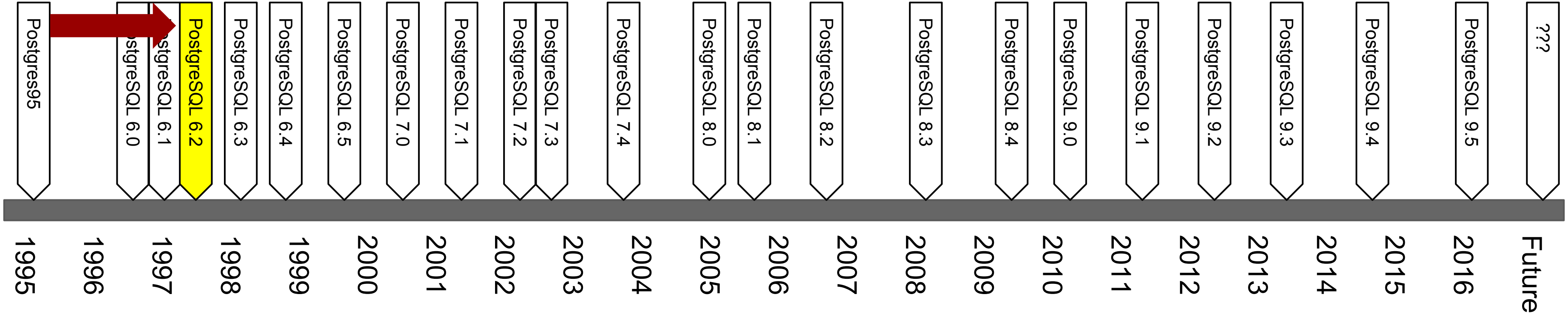


PostgreSQL 6.2 - Use quicksort when data fits in memory



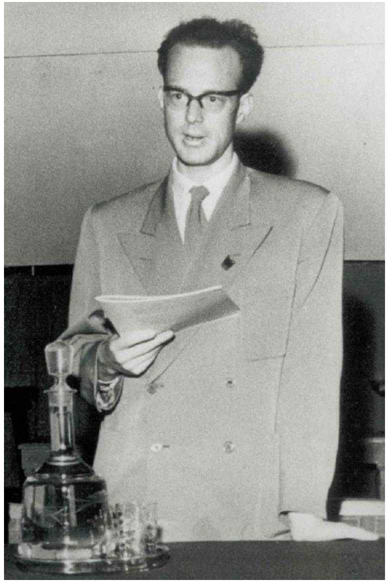
```
commit 712ea2507ef7f3ea4a7149962c85de0b35245a64
Author: Vadim B. Mikheev <vadim4o@yahoo.com>
Date:   Thu Sep 18 05:37:31 1997 +0000

     1. Use qsort for first run
     2. Limit number of tuples in leftist trees:
     - put one tuple from current tree to disk if limit reached;
     - end run creation if limit reached by nextrun.
     3. Avoid mergeruns() if first run is single one!
```



A quick digression -- Quicksort

- Invented in 1959 by Tony Hoare
- In-memory only algorithm
- $n \cdot \log(n)$ average run-time
- Very low constant factor
- Very efficient use of CPU cache and registers
- “Cache-oblivious”
  - Does not depend on tuning for specific cache sizes
- Available in standard C library
- Has $O(n^2)$ worst-case (but unlikely)
  - Worse cases tend to happen in cases like partially sorted data or “organ-pipe” data (increasing then decreasing).
  - Various strategies to mitigate -- choice of pivot, randomizing inputs

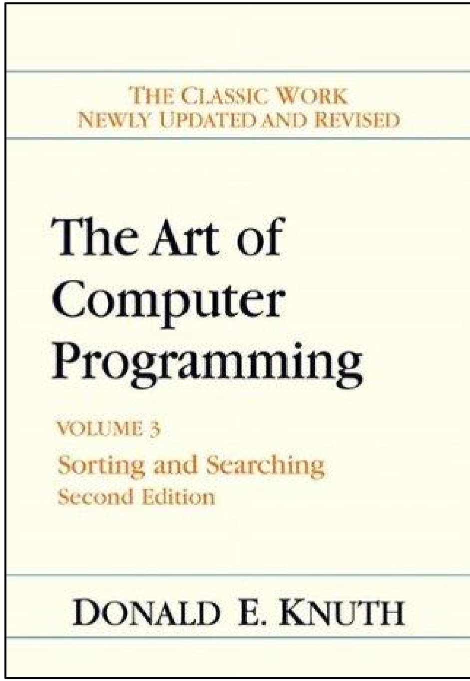


Tony Hoare

A longer digression -- Replacement Selection

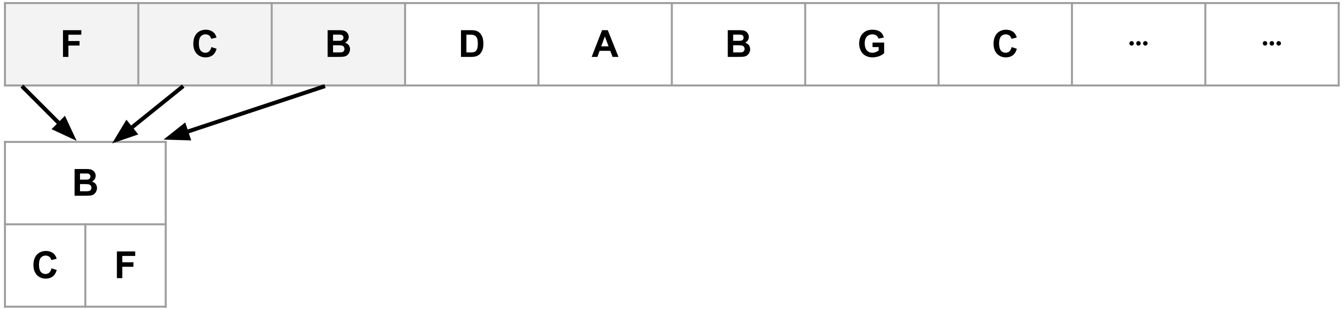
Postgres implements an external sort using Replacement Selection with Polyphase Merge straight out of Knuth first published in 1973.

- External (on-disk) sort which works with a limited subset of the data in-memory at any one time
- Writes data out to disk in sorted runs then reads it back into memory to merge into longer runs
- Repeats the merge process until only one tape is left
- Replacement selection (R1-R3)--Knuth, Vol.3, p.257
- Polyphase merge Alg.D (D1-D6)--Knuth, Vol.3, p.270-271



It always generates files on disk for temporary runs and always generates a new file on disk for the resulting sorted relation.

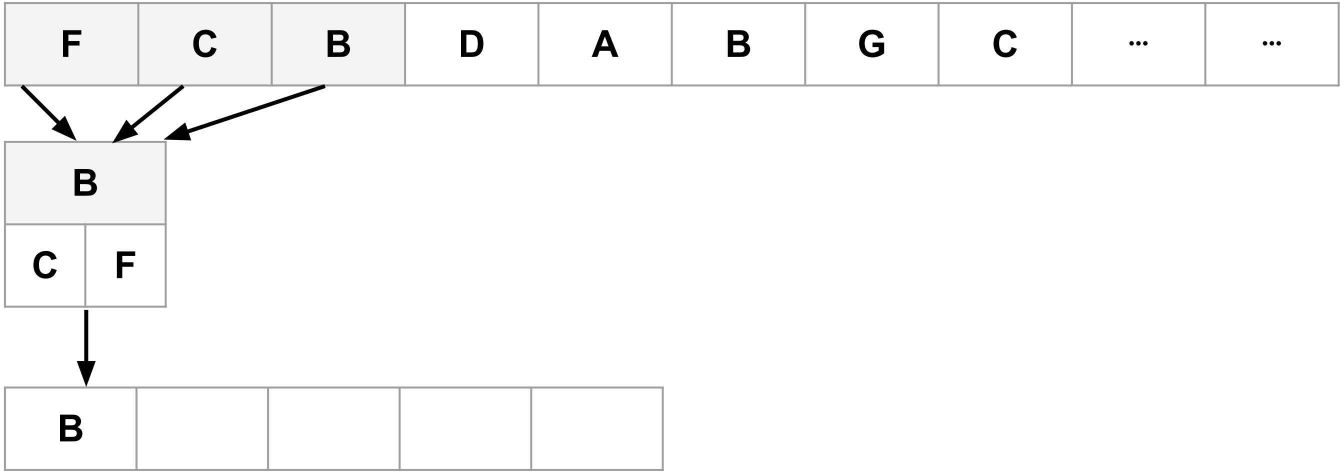
Replacement Selection: Generate Runs



❖ Load as many values as possible in working memory (work_mem)

❖ Build a priority queue using a heap

Replacement Selection: Generate Runs



- Load as many values as possible in working memory (work_mem)
- Build a priority queue using a heap
- Extract Lowest value and output to a sorted “run”

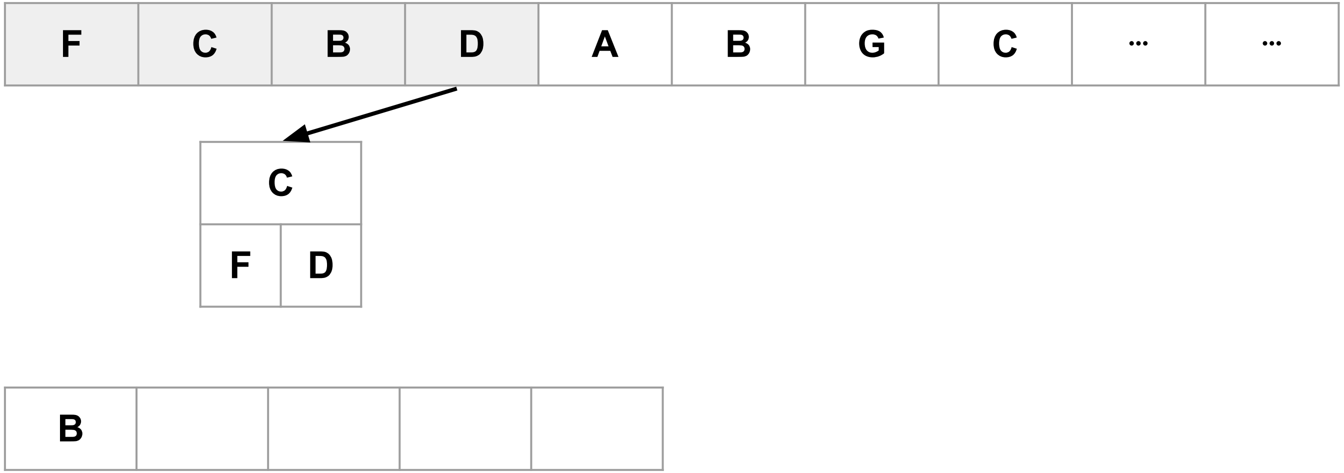
Replacement Selection: Generate Runs

F	C	B	D	A	B	G	C	...	...

C	
F	

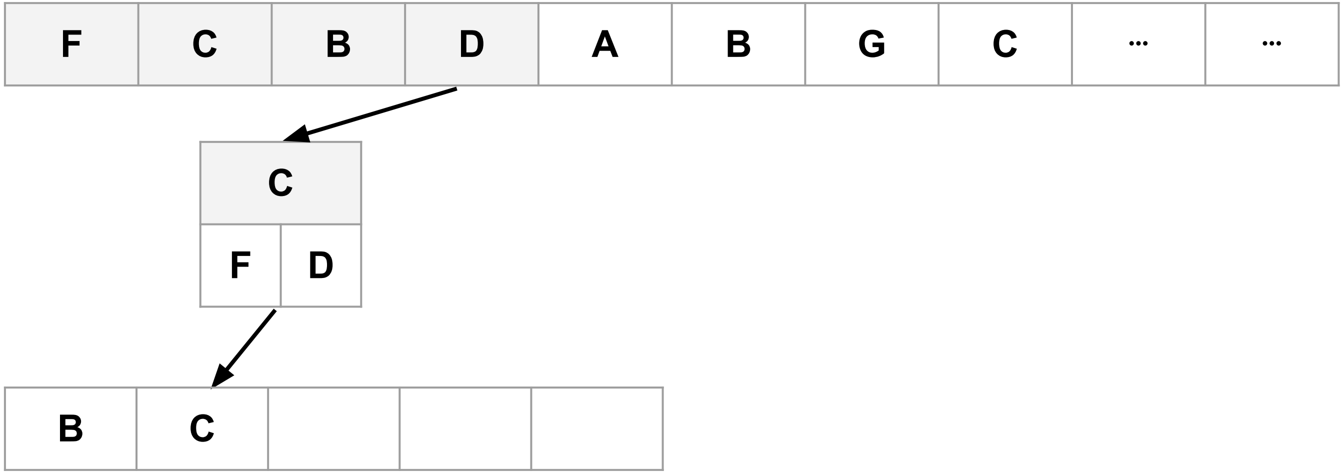
B				

Replacement Selection: Generate Runs



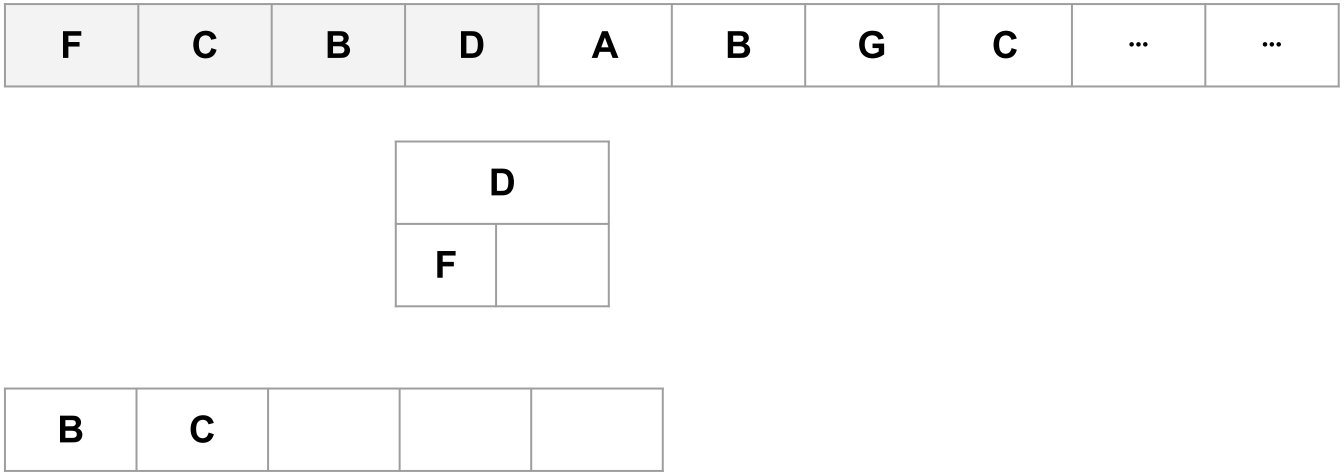
❖ Load next value from input stream to replace value that was output to run

Replacement Selection: Generate Runs



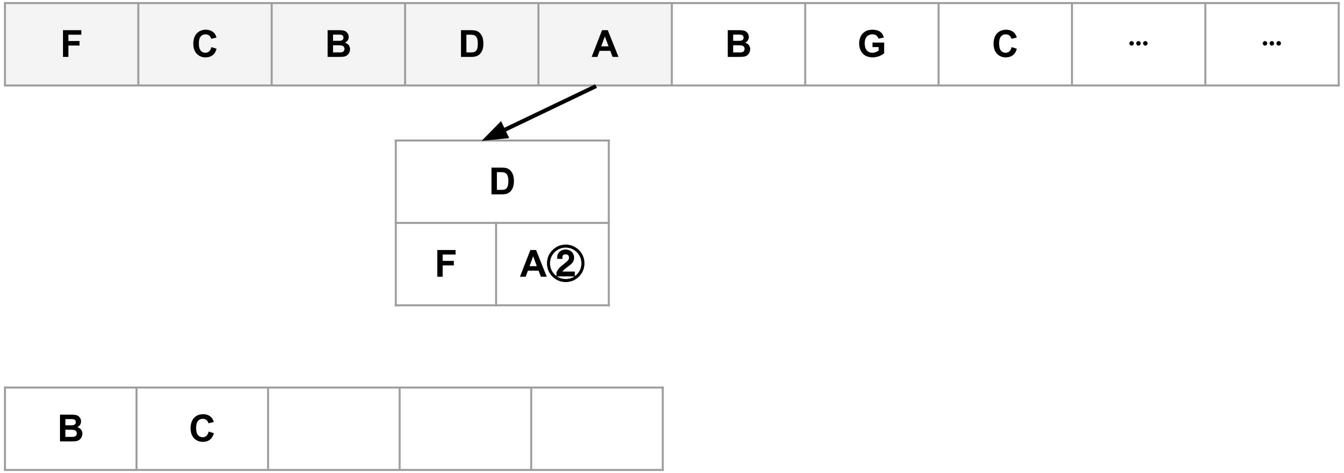
- Load next value from input stream to replace value that was output to run
- Output new lowest value to sorted run

Replacement Selection: Generate Runs



- ❖ We see that it's "too late" for A as we have already output values later than A.
- ❖ Instead we must save A for later and output A in a later run

Replacement Selection: Generate Runs



- ❖ We see that it’s “too late” for A as we have already output values later than A.
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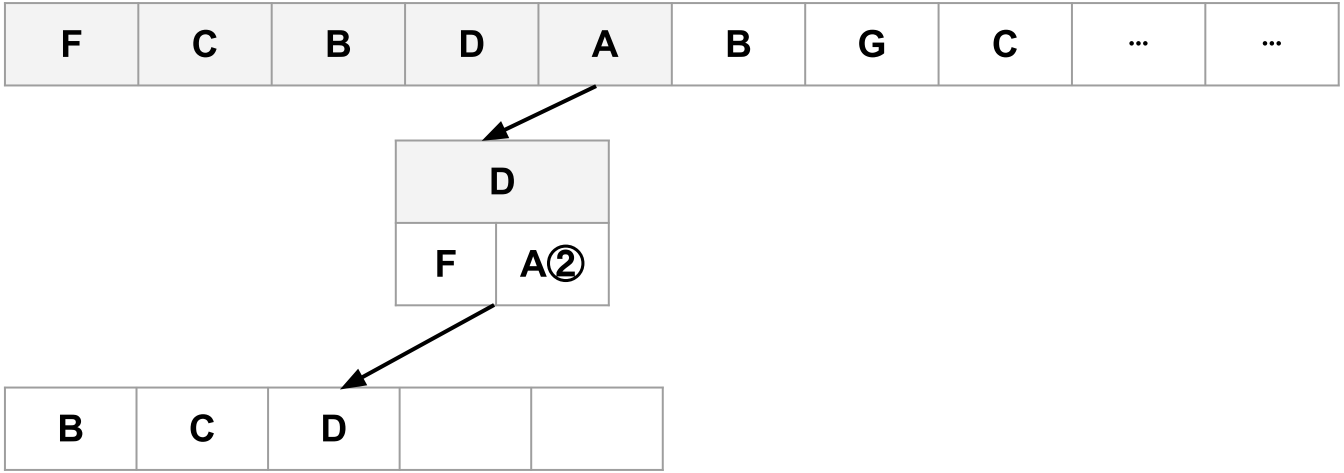
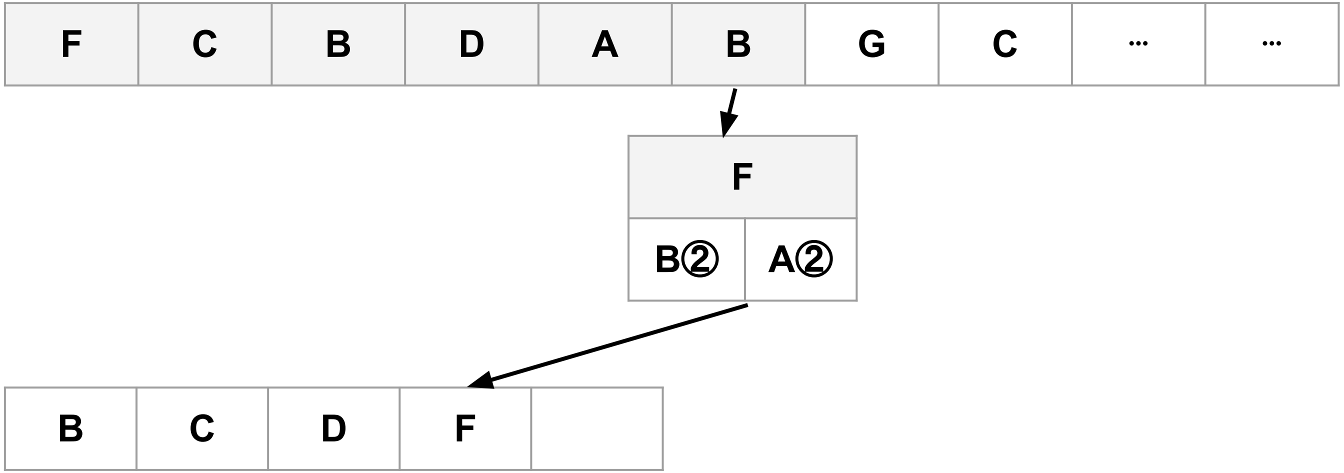
Replacement Selection: Generate Runs



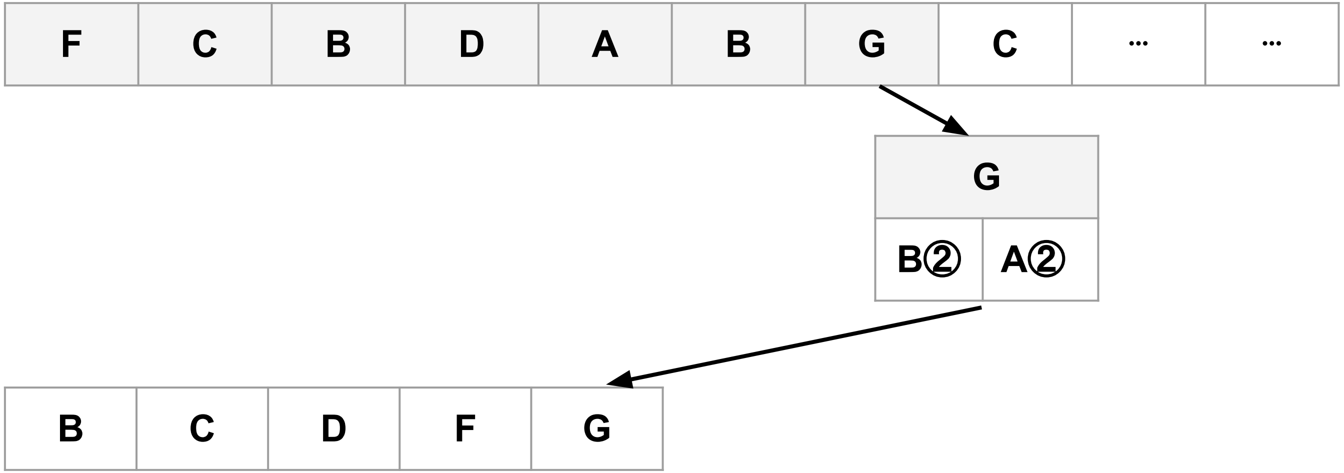
- We see that it’s “too late” for A as we have already output values later than A.
- Instead we must save A for later and output A in a later run
- Continue outputting values for the current sorted run

Replacement Selection: Generate Runs



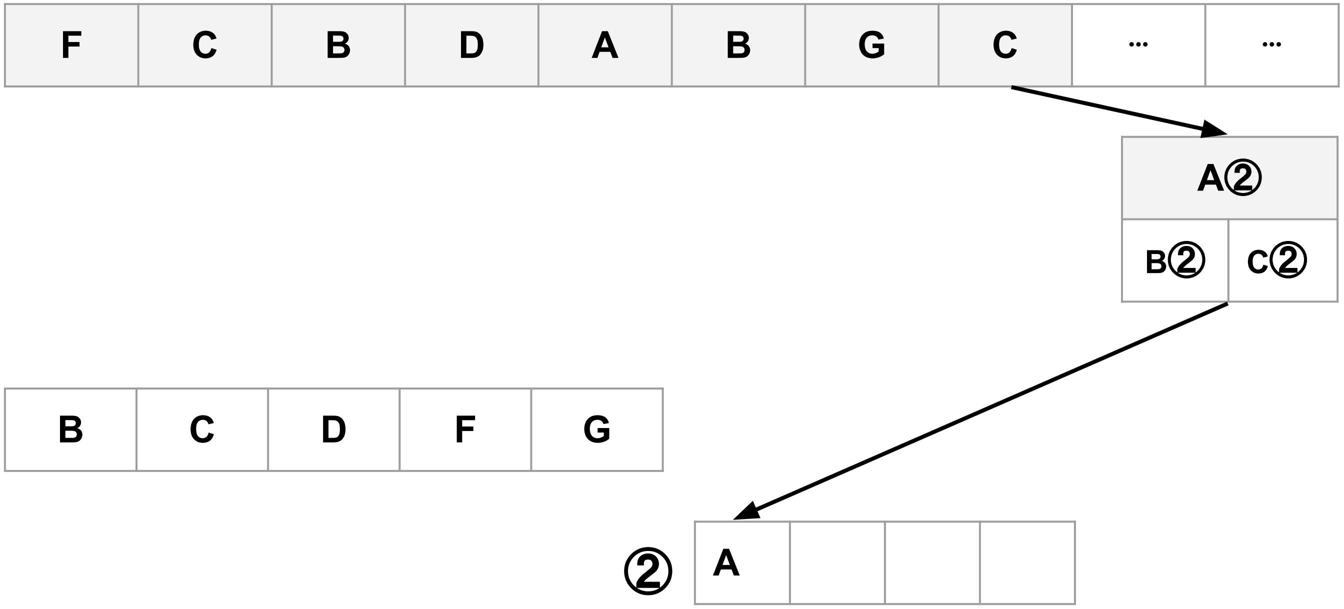
- We see that it's "too late" for A as we have already output values later than A.
- Instead we must save A for later and output A in a later run
- Similarly we must save B for run 2
- But we can still output F in this run

Replacement Selection: Generate Runs



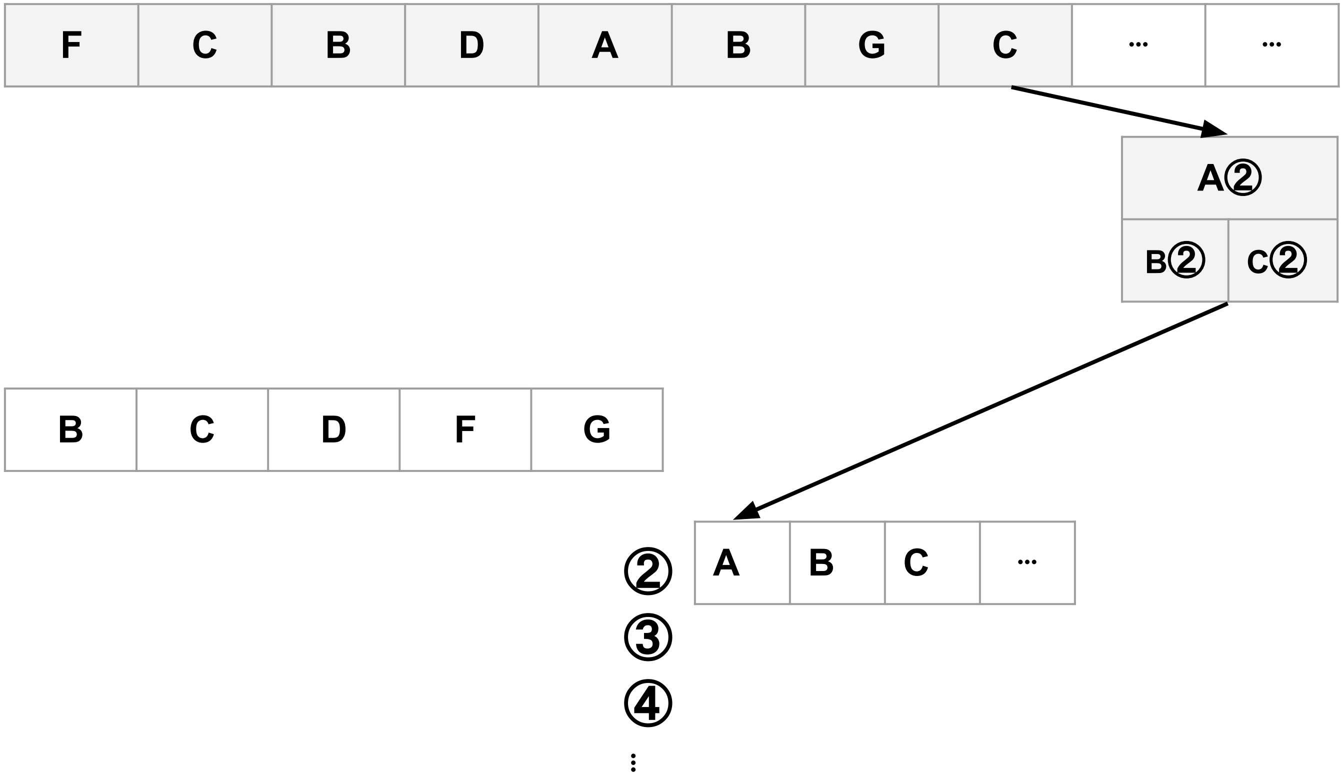
- We see that it's "too late" for A as we have already output values later than A.
- Instead we must save A for later and output A in a later run
- Similarly we must save B for run 2
- But we can still output F in this run
- And we can see that G is still not too late for current run

Replacement Selection: Generate Runs

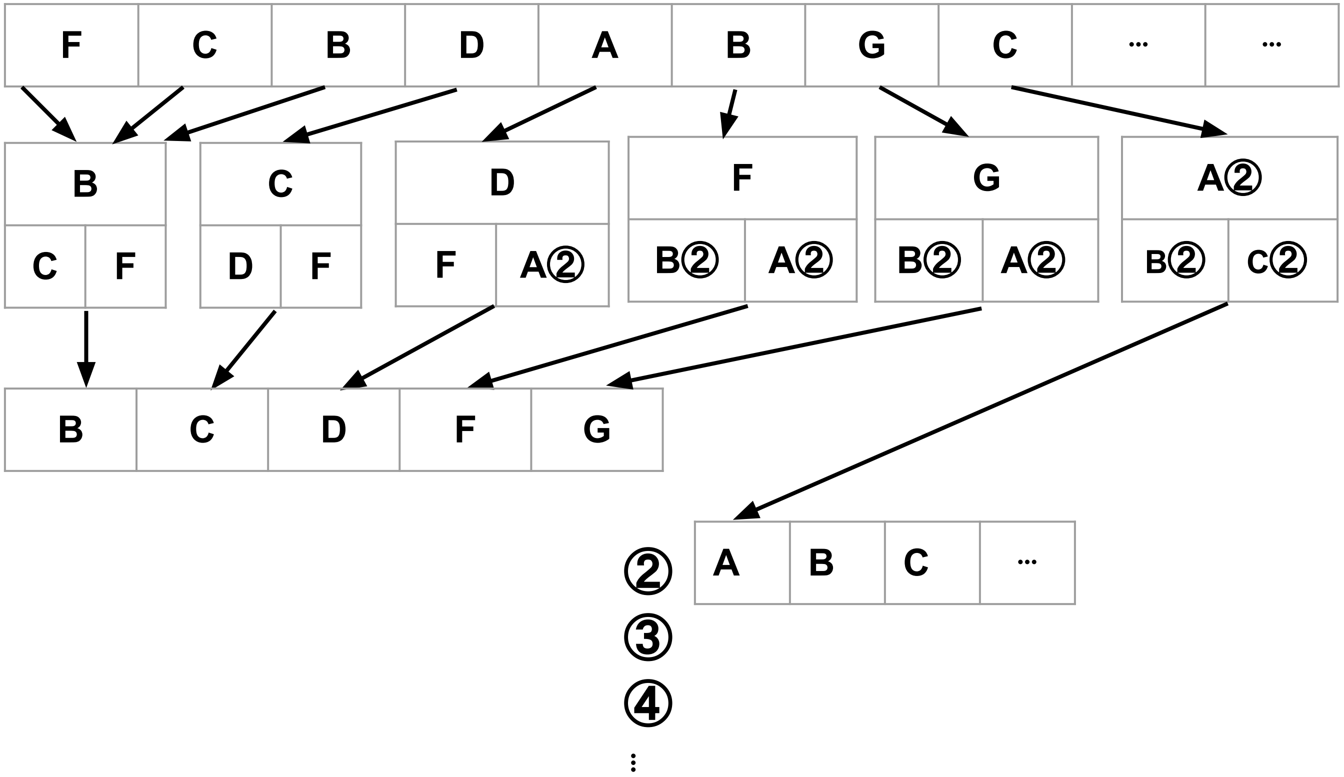


- Eventually all values are saved for run 2
- Output lowest value in new sorted run

Replacement Selection: Generate Runs



Replacement Selection: Generate Runs

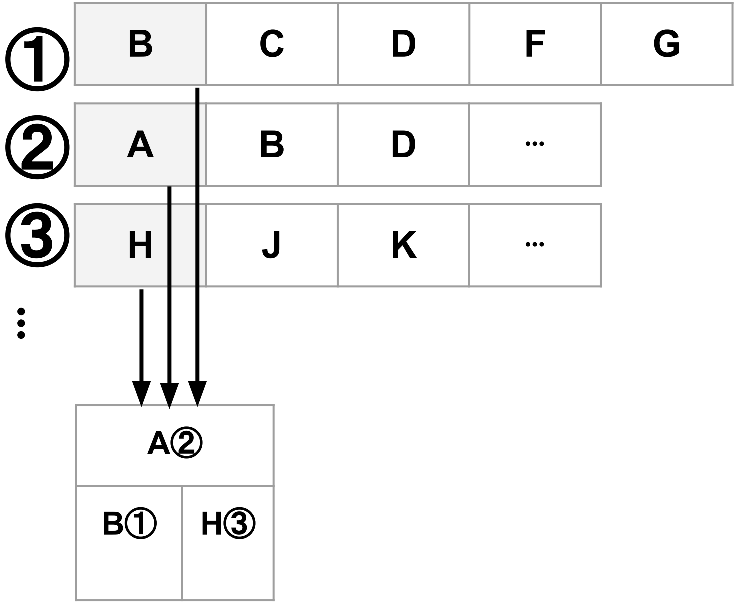


Replacement Selection: Merge Runs

①	B	C	D	F	G
②	A	B	D	…	
③	H	J	K	…	
⋮					

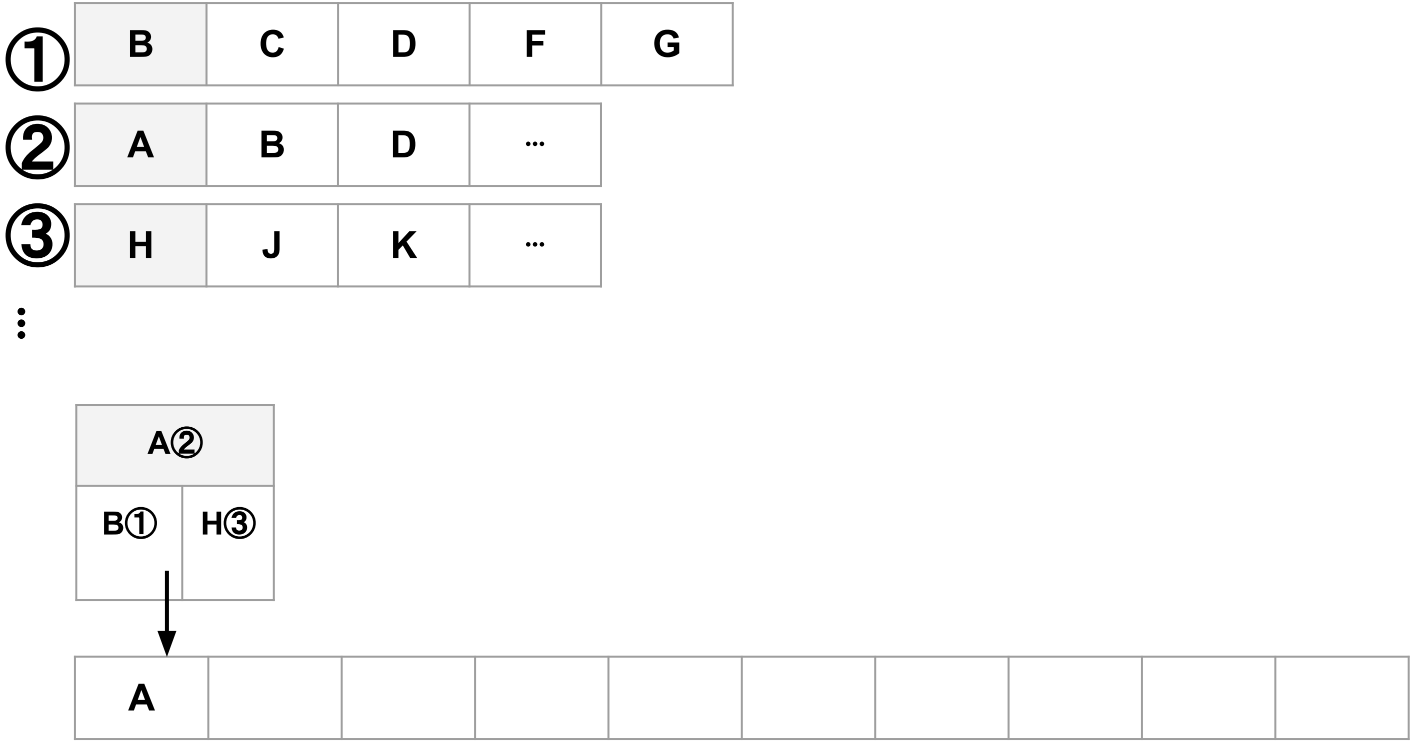
❖ We must then merge many sorted runs into longer sorted runs

Replacement Selection: Merge Runs



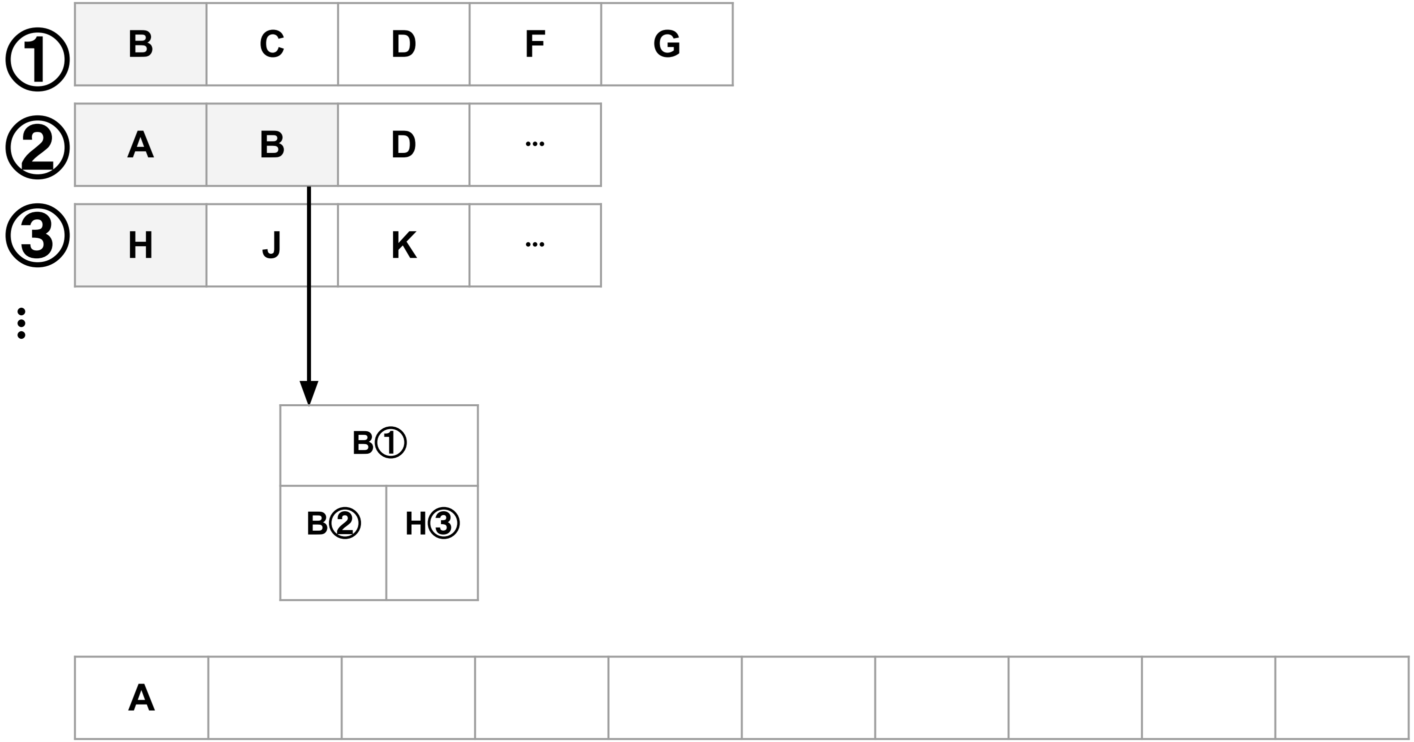
- We must then merge many sorted runs into longer sorted runs
- We load first element from sorted runs into priority queue (heap)
- We mark each element with which run it came from

Replacement Selection: Merge Runs



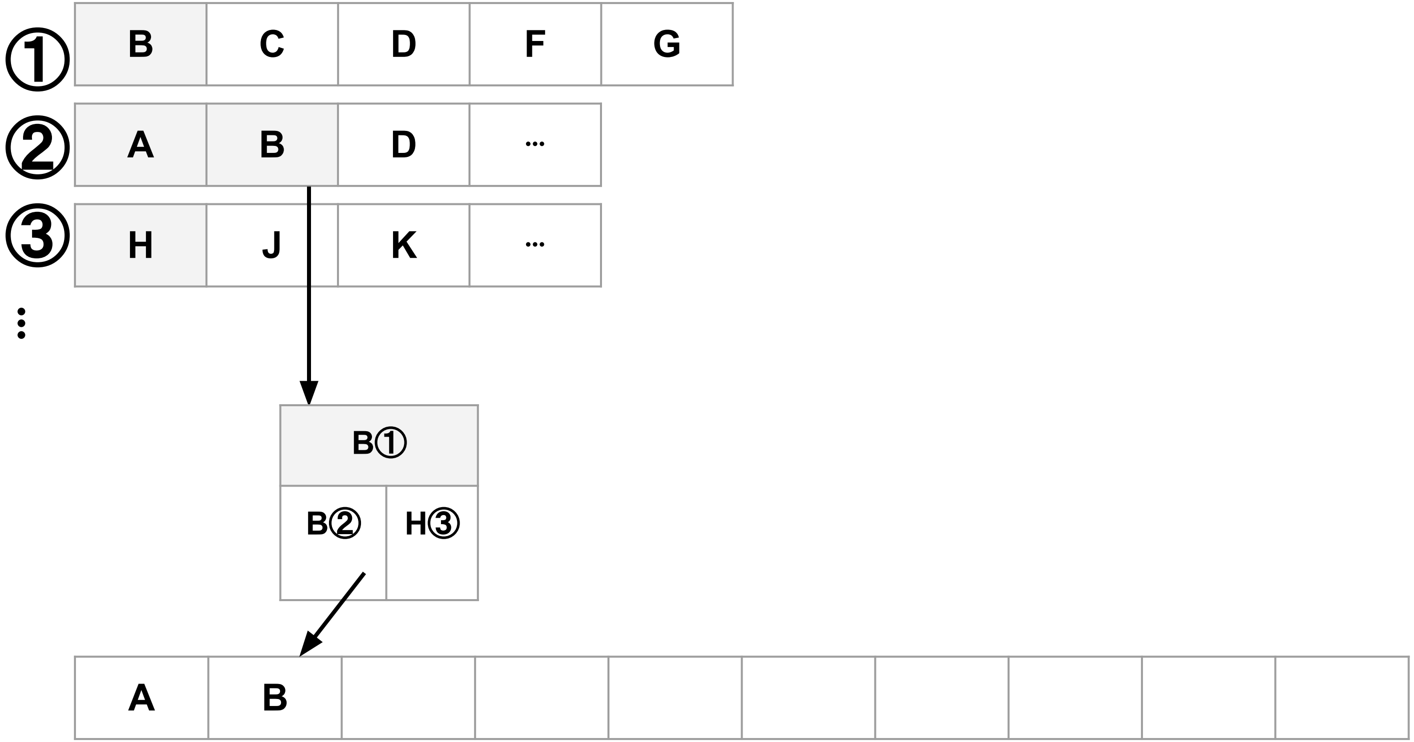
❖ Output lowest value to merged run

Replacement Selection: Merge Runs



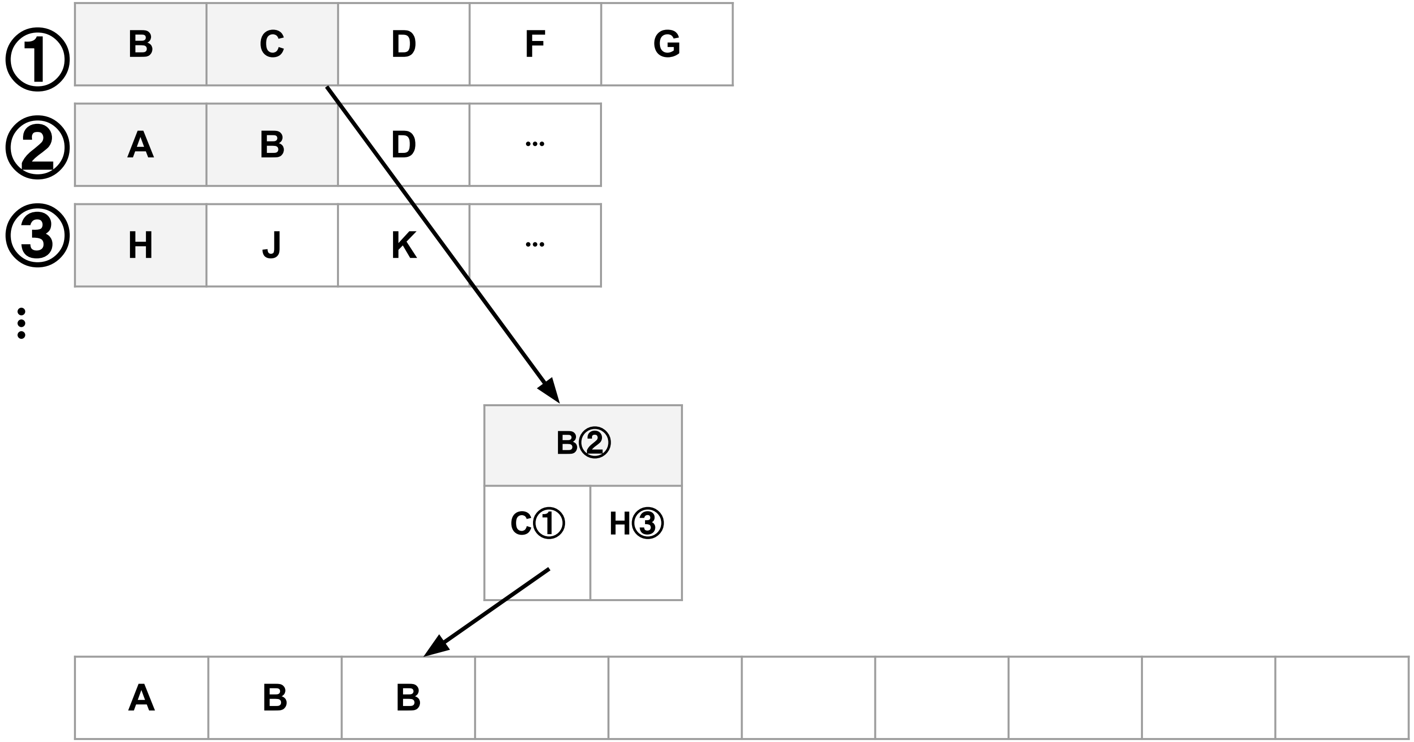
- ❖ Output lowest value to merged run
- ❖ Replace value with next value from the same run

Replacement Selection: Merge Runs



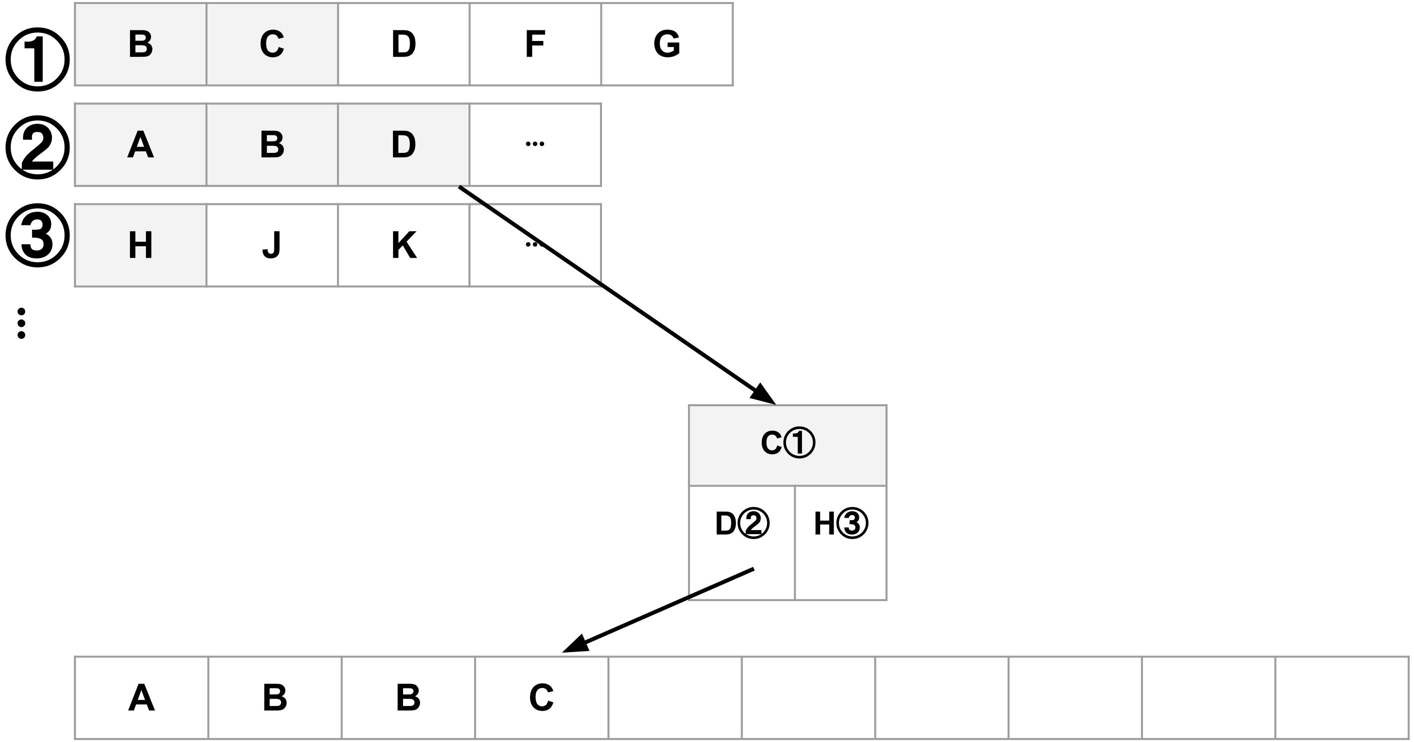
- Repeat outputting lowest value and replacing with next value from that sorted run

Replacement Selection: Merge Runs



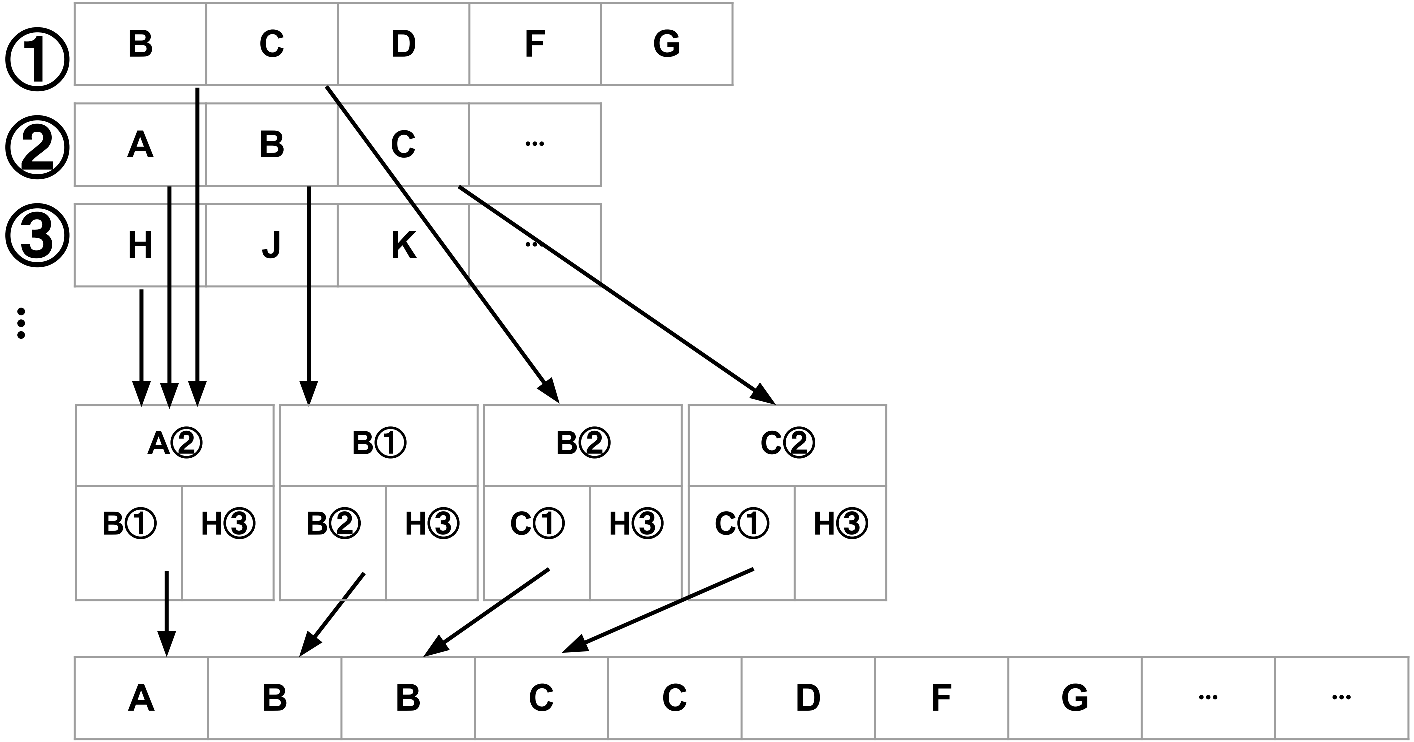
- Repeat outputting lowest value and replacing with next value from that sorted run

Replacement Selection: Merge Runs



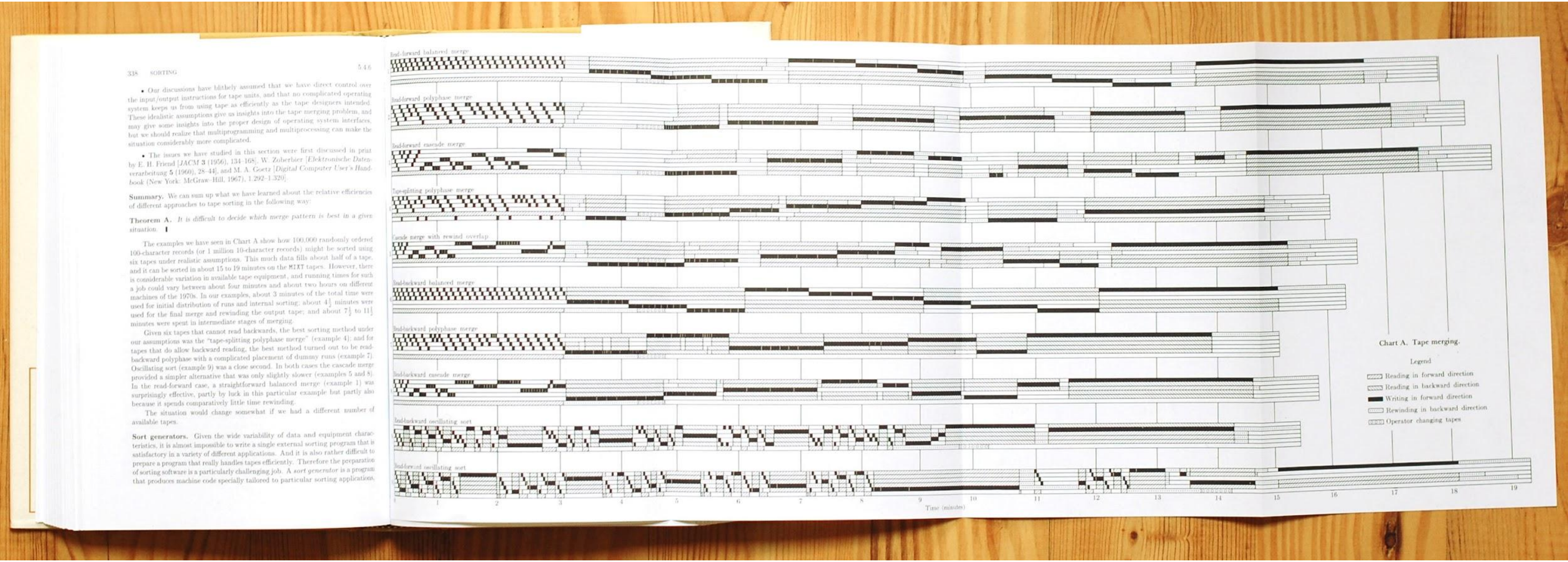
- Repeat outputting lowest value and replacing with next value from that sorted run

Replacement Selection: Merge Runs



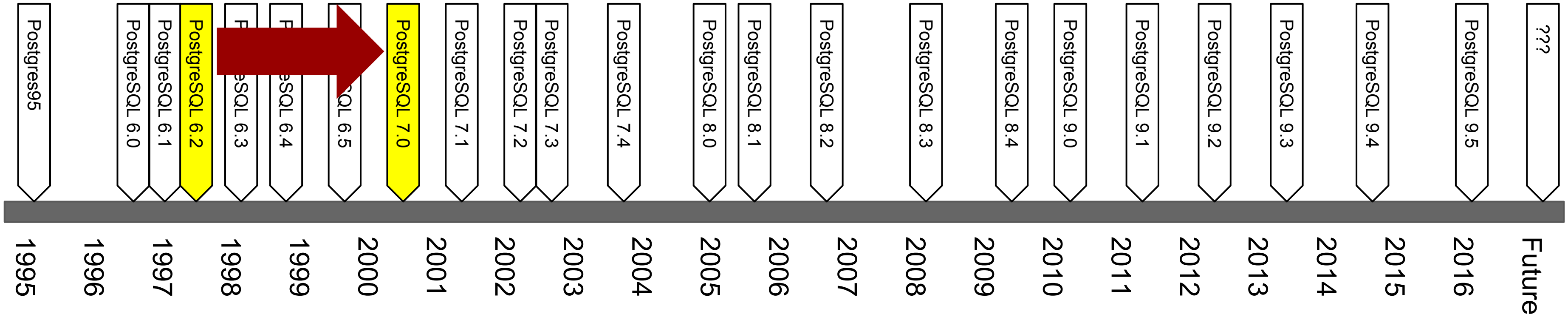
- ❖ This generates a longer sorted run containing all the elements from the runs we merged
- ❖ Repeat this process recursively until there's only a single long sorted run remaining with all data

Replacement Selection: Merge Scheduling



- Knuth dedicated a special pull-out section of his book to various orders in which to merge runs
- Each of these is a different strategy with different advantages and disadvantages
- Some depend on being able to read tapes backwards or have an operator change tapes
- They all assume you have a small fixed number of tape drives

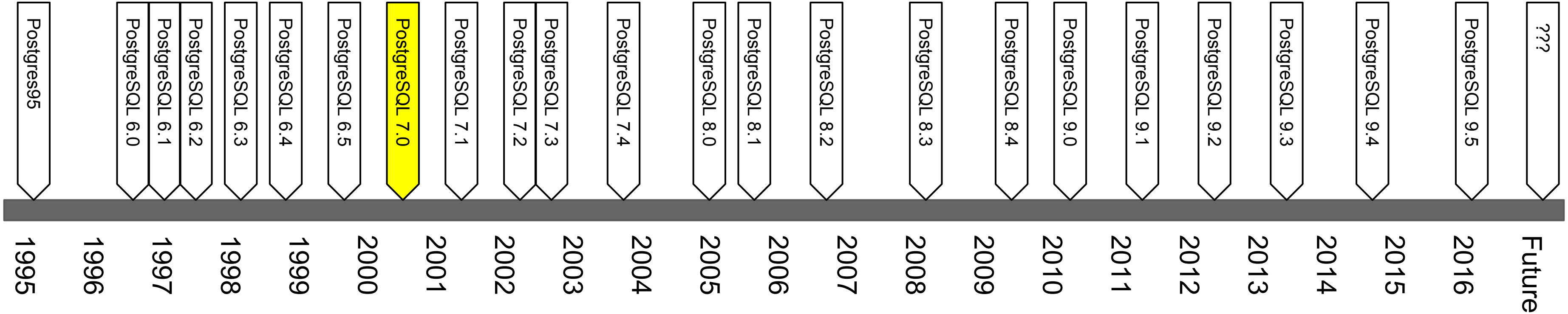
PostgreSQL 6.2 to 7.0 -- Two years go by



PostgreSQL 7.0 - Major rewrite of psort. turns it into tuplesort.c

Tom Lane

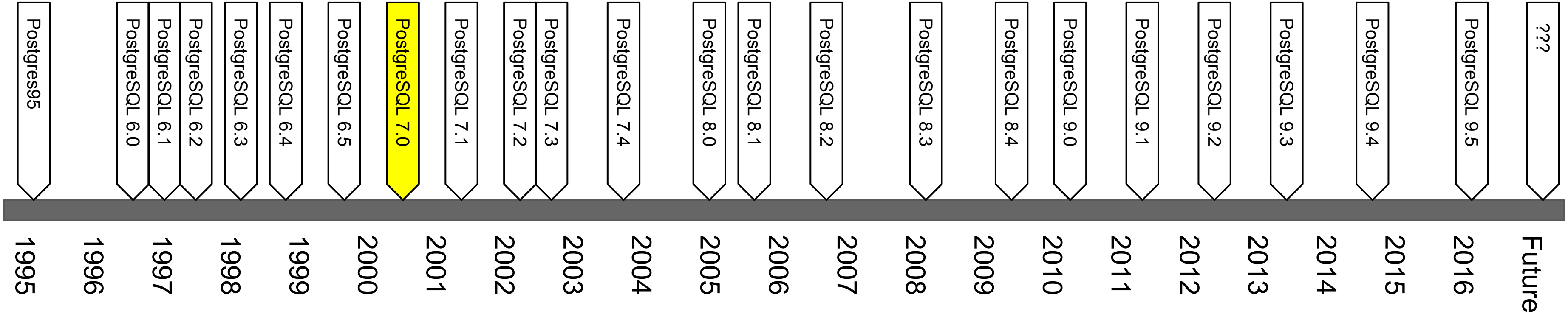

```
commit db3c4c3a2d980dcdd9a19feeddd11230587f0d21
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Wed Oct 13 15:02:32 1999 +0000

    Split 'BufFile' routines out of fd.c into a new module, buffile.c.  Extend
    BufFile so that it handles multi-segment temporary files transparently.
    This allows sorts and hashes to work with data exceeding 2Gig (or whatever
    the local limit on file size is).  Change psort.c to use relative seeks
    instead of absolute seeks for backwards scanning, so that it won't fail
    when the data volume exceeds 2Gig.
```



PostgreSQL 7.0 - Reuse space aggressively

Tom Lane

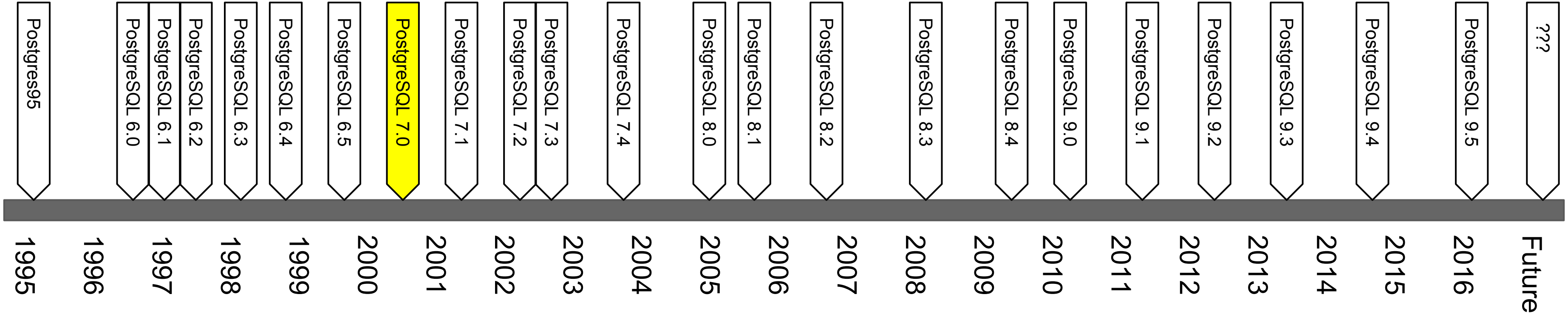

```
commit 957146dcec9cc2fb31220c26c51802623df04e5e
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Sat Oct 16 19:49:28 1999 +0000

    Second phase of psort reconstruction project: add bookkeeping logic to
    recycle storage within sort temp file on a block-by-block basis.  This
    reduces peak disk usage to essentially just the volume of data being
    sorted, whereas it had been about 4x the data volume before.
```



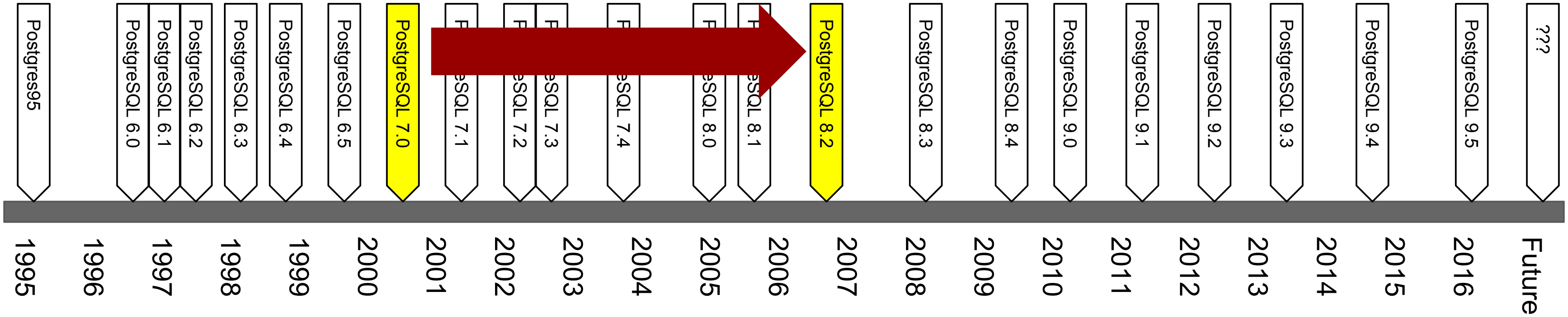
PostgreSQL 7.0 - General purpose module for queries and index builds

Tom Lane

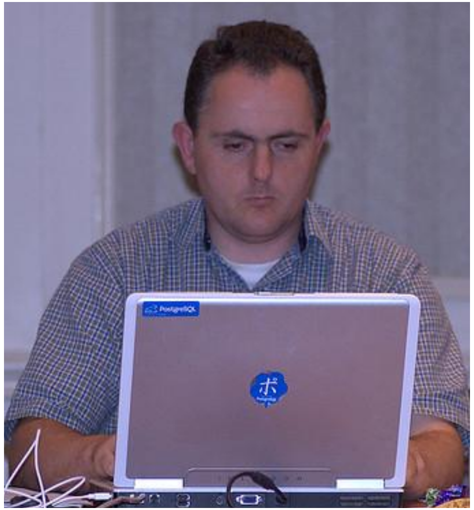

```
commit 26c48b5e8cffafaf3b8acf345ca9fd8a1e408a54
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Sun Oct 17 22:15:09 1999 +0000

    Final stage of psort reconstruction work: replace psort.c with
    a generalized module 'tuplesort.c' that can sort either HeapTuples or
    IndexTuples, and is not tied to execution of a Sort node.  Clean up
    memory leakages in sorting, and replace nbtsort.c's private implementation
    of mergesorting with calls to tuplesort.c.
```



PostgreSQL 7.0 to 8.2 -- **Six** years go by!

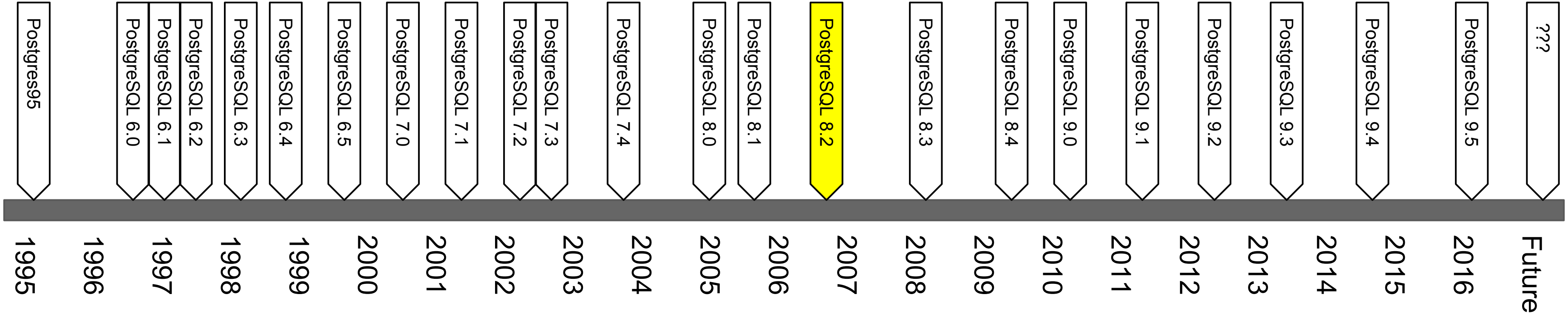


PostgreSQL 8.2 - Virtual Tape Drives Are Cheaper than Real Drives



Simon Riggs

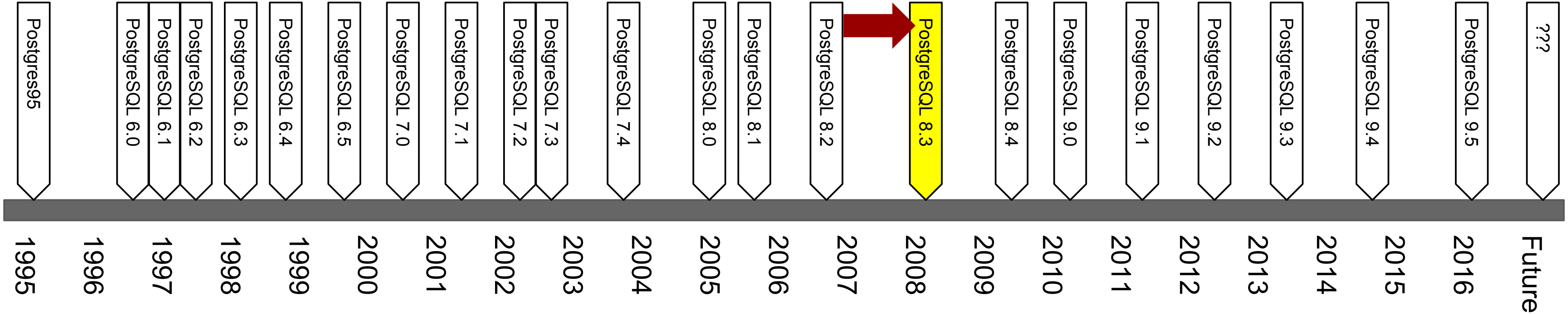

```
commit df700e6b40195d28dc764e0c694ac8cef90d4638
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Sun Feb 19 05:54:06 2006 +0000

    Improve tuplesort.c to support variable merge order.  The original coding
    with fixed merge order (fixed number of "tapes") was based on obsolete
    assumptions, namely that tape drives are expensive.  Since our "tapes"
    are really just a couple of buffers, we can have a lot of them given
    adequate workspace.  This allows reduction of the number of merge passes
    with consequent savings of I/O during large sorts.

    Simon Riggs with some rework by Tom Lane
```



PostgreSQL 8.3 - “External Merge” saves a round trip to disk

Gregory Stark


```
commit 2415ad983174164ff30ce487c0e6b4b53321b83a
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Mon May 21 17:57:35 2007 +0000

    Teach tuplestore.c to throw away data before the "mark" point when the caller
    is using mark/restore but not rewind or backward-scan capability.  Insert a
    materialize plan node between a mergejoin and its inner child if the inner
    child is a sort that is expected to spill to disk.  The materialize shields
    the sort from the need to do mark/restore and thereby allows it to perform
    its final merge pass on-the-fly; while the materialize itself is normally
    cheap since it won't spill to disk unless the number of tuples with equal
    key values exceeds work_mem.

    Greg Stark, with some kibitzing from Tom Lane.
```

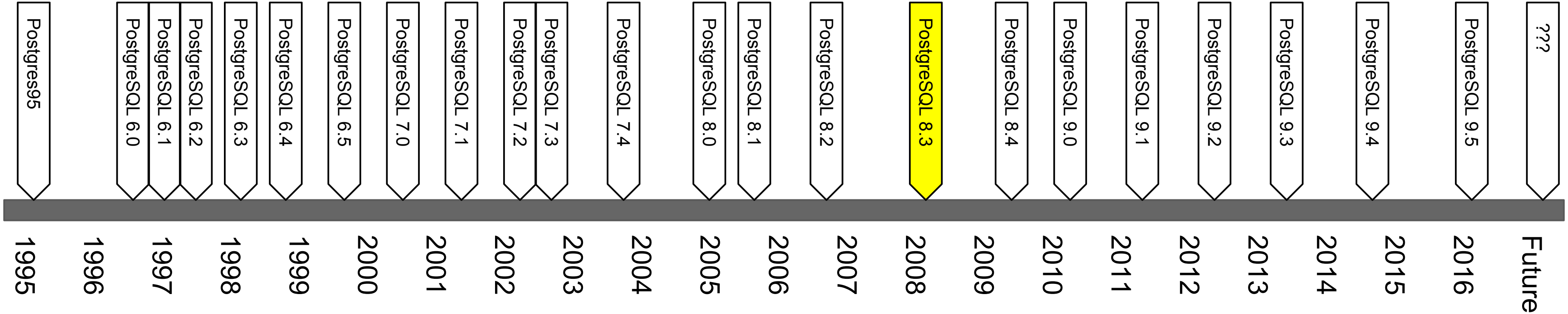


PostgreSQL 8.3 - Top-N sorting

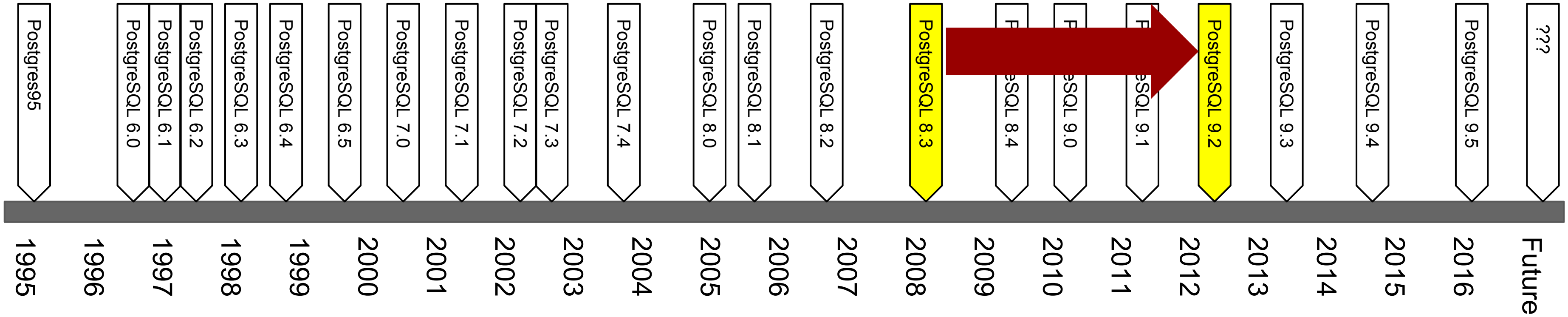
Gregory Stark

© Oleg Bartunov

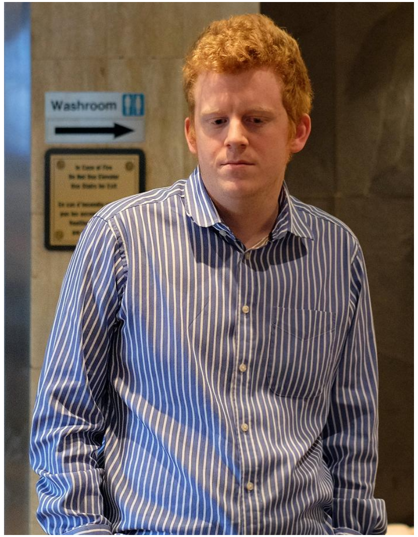
```
commit d26559dbf356736923b26704ce76ca820ff3a2b0
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Fri May 4 01:13:45 2007 +0000

    Teach tuplesort.c about "top N" sorting, in which only the first N tuples
    need be returned.  We keep a heap of the current best N tuples and sift-up
    new tuples into it as we scan the input.  For M input tuples this means
    only about M*log(N) comparisons instead of M*log(M), not to mention a lot
    less workspace when N is small --- avoiding spill-to-disk for large M
    is actually the most attractive thing about it.  Patch includes planner
    and executor support for invoking this facility in ORDER BY ... LIMIT
    queries.  Greg Stark, with some editorialization by moi.
```



PostgreSQL 8.3 to 9.2 -- Four years go by...



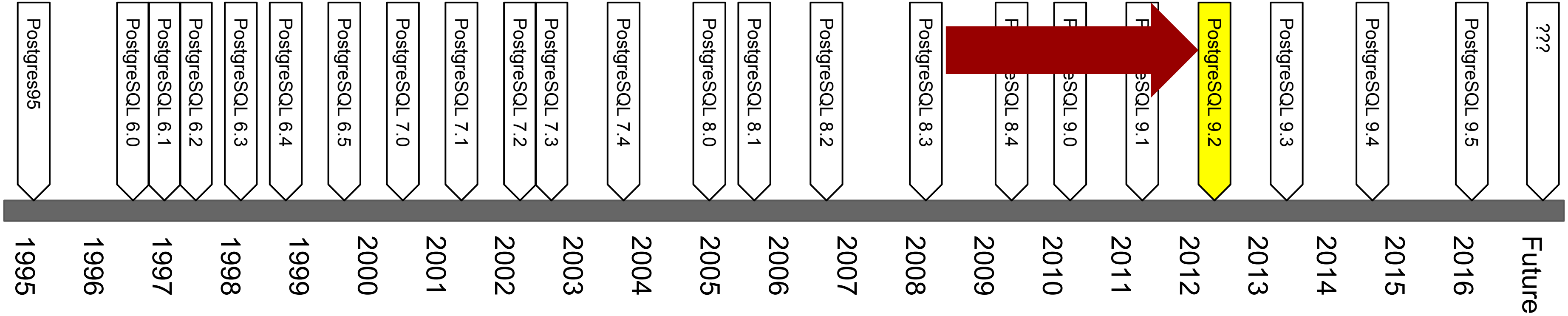
PostgreSQL 9.2 - SortSupport



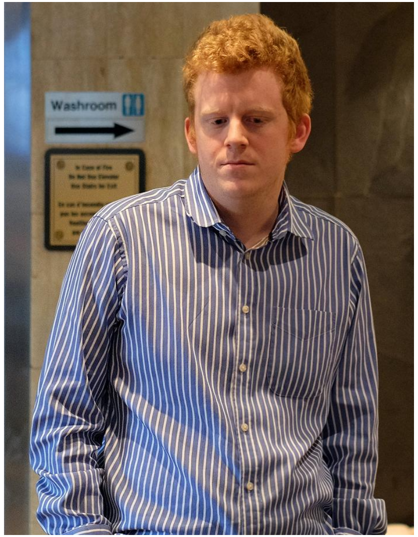
Peter Geoghegan

© Oleg Bartunov

```
commit c6e3ac11b60ac4a8942ab964252d51c1c0bd8845
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Wed Dec 7 00:18:38 2011 -0500

    Create a "sort support" interface API for faster sorting.

    This patch creates an API whereby a btree index opclass can optionally
    provide non-SQL-callable support functions for sorting.  In the initial
    patch, we only use this to provide a directly-callable comparator function,
    which can be invoked with a bit less overhead than the traditional
    SQL-callable comparator.  While that should be of value in itself, the real
    reason for doing this is to provide a datatype-extensible framework for
    more aggressive optimizations, as in Peter Geoghegan's recent work.

    Robert Haas and Tom Lane
```

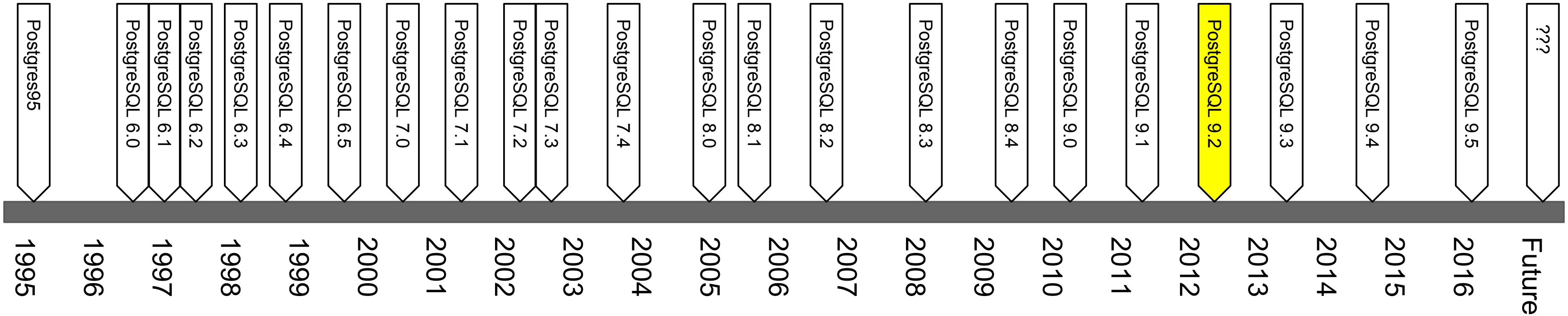


PostgreSQL 9.2 - Specialized quicksorts with inlined comparators



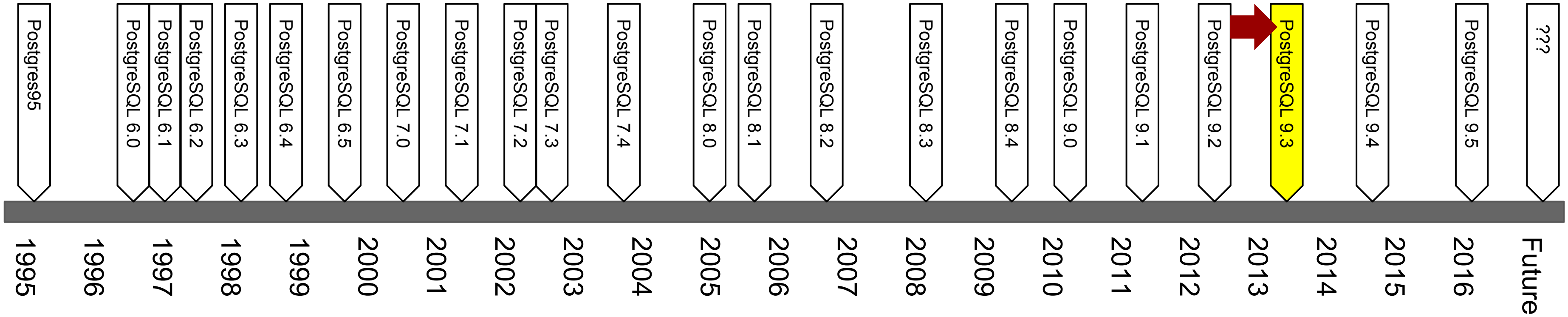
Peter Geoghegan


```
commit 337b6f5ecf05b21b5e997986884d097d60e4e3d0
Author: Robert Haas <rhaas@postgresql.org>
Date:   Wed Feb 15 12:13:32 2012 -0500

    Speed up in-memory tuplesorting.

    Per recent work by Peter Geoghegan, it's significantly faster to
    tuplesort on a single sortkey if ApplySortComparator is inlined into
    quicksort rather reached via a function pointer.  It's also faster
    in general to have a version of quicksort which is specialized for
    sorting SortTuple objects rather than objects of arbitrary size and
    type.  This requires a couple of additional copies of the quicksort
    logic, which in this patch are generate using a Perl script.  There
    might be some benefit in adding further specializations here too,
    but thus far it's not clear that those gains are worth their weight
    in code footprint.
```



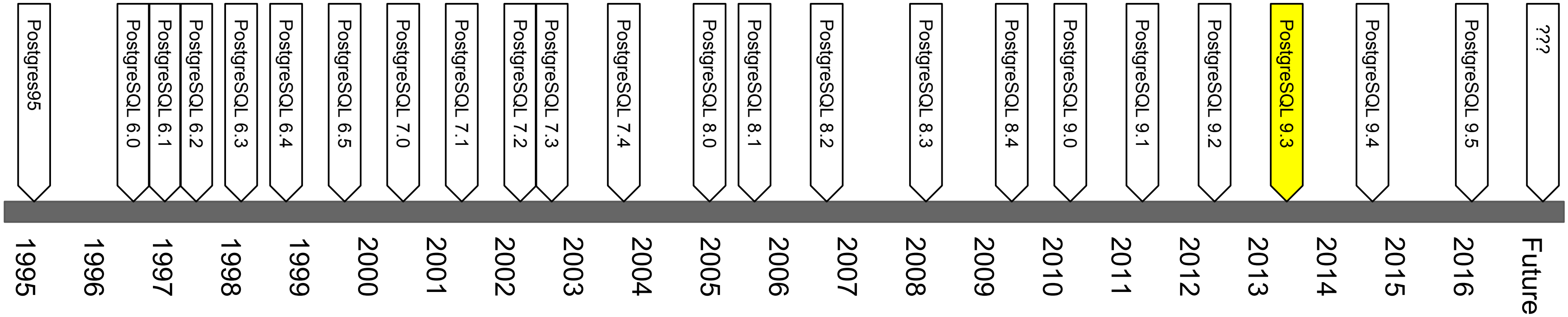
PostgreSQL 9.3 - Use all of work_mem for large sorts

```
commit 8ae35e91807508872cabd3b0e8db35fc78e194ac
Author: Tom Lane <tgl@sss.pgh.pa.us>
Date:   Thu Jan 17 13:12:14 2013 -0500

    Improve memory space management in tuplesort and tuplestore.

    The code originally just doubled the size of the tuple-pointer array so
    long as that would fit in allowedMem.  This could result in failing to use
    as much as half of allowedMem, if (as is typical) the last doubling attempt
    didn't quite fit.  Worse, we might double the array size but be unable to
    use most of the added slots, because there was no room left within the
    allowedMem limit for tuples the slots should point to.  To fix, double only
    so long as we've used less than half of allowedMem in total.  Then do one
    more array enlargement, but scale it based on total memory consumption so
    far.  This will work nicely as long as the average tuple size is reasonably
    stable, and in any case should be better than the old method.
```

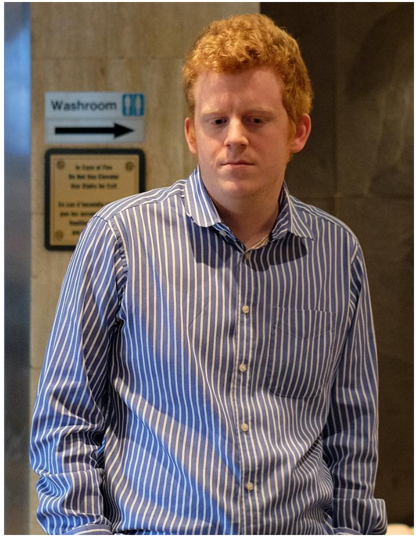


PostgreSQL 9.3 - Allow using more than 2GB for sorts

```
commit 263865a48973767ce8ed7b7788059a38a24a9f37
Author: Noah Misch <noah@leadboat.com>
Date:   Thu Jun 27 14:53:57 2013 -0400

    Permit super-MaxAllocSize allocations with MemoryContextAllocHuge().

    The MaxAllocSize guard is convenient for most callers, because it
    reduces the need for careful attention to overflow, data type selection,
    and the SET_VARSIZE() limit.  A handful of callers are happy to navigate
    those hazards in exchange for the ability to allocate a larger chunk.
    Introduce MemoryContextAllocHuge() and repalloc_huge().  Use this in
    tuplesort.c and tuplestore.c, enabling internal sorts of up to INT_MAX
    tuples, a factor-of-48 increase.  In particular, B-tree index builds can
    now benefit from much-larger maintenance_work_mem settings.

    Reviewed by Stephen Frost, Simon Riggs and Jeff Janes.
```

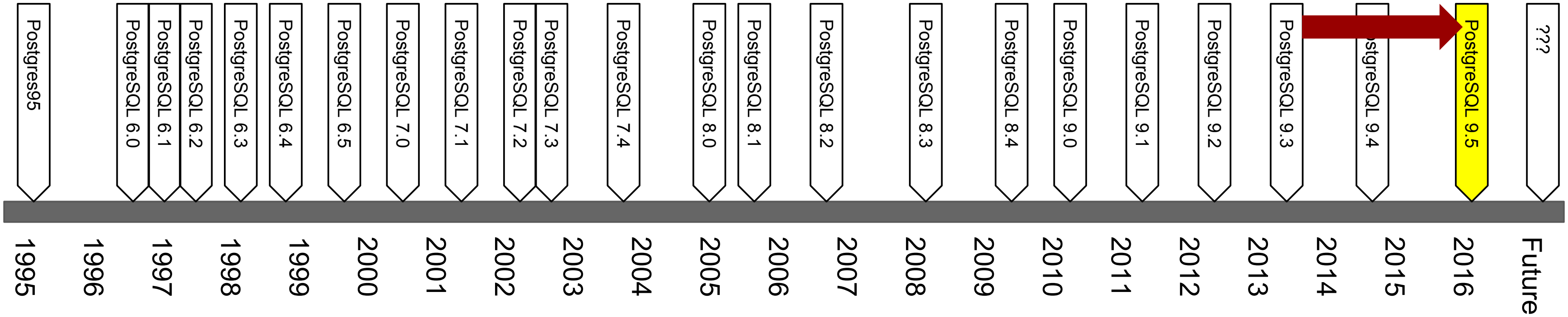


PostgreSQL 9.5 - Quicksort specializations with inlined comparators



Peter Geoghegan


```
commit 4ea51cdfe85ceef8afabceb03c446574daa0ac23
Author: Robert Haas <rhaas@postgresql.org>
Date:   Mon Jan 19 15:20:31 2015 -0500

    Use abbreviated keys for faster sorting of text datums.

    This commit extends the SortSupport infrastructure to allow operator
    classes the option to provide abbreviated representations of Datums;
    in the case of text, we abbreviate by taking the first few characters
    of the strxfrm() blob.  If the abbreviated comparison is insufficent
    to resolve the comparison, we fall back on the normal comparator.
    This can be much faster than the old way of doing sorting if the
    first few bytes of the string are usually sufficient to resolve the
    comparison.
```



Abbreviated Keys For Text Data

```
strcoll("Олег Бартунов", "Магнус Хагандер") == 3
 => "Олег Бартунов" > "Магнус Хагандер"
```

- strcoll can be very slow because comparison rules can be very complicated
- Even when comparing ASCII it is much slower than integer comparisons

```
strxfrm("Олег Бартунов")
 => C393C38EC382C2BEC2BCC2BBC395C397C39AC391C393C2BD01...
strxfrm("Магнус Хагандер")
 => C390C2BBC2BEC391C39AC396C39DC2BBC2BEC2BBC391C2BFC3...
```

- Result from strxfrm can be compared quickly using memcmp
- But result can be very large which requires more memory and disk

Abbreviated Keys For Text Data

- Use first 8 bytes (4 bytes on 32-bit platforms) as integer for fast comparisons

```
strxfrm("Олег Бартунов")
 => C393C38EC382C2BEC2BCC2BBC395C397C39AC391C393C2BD01...
strxfrm("Магнус Хагандер")
 => C390C2BBC2BEC391C39AC396C39DC2BBC2BEC2BBC391C2BFC3...
0xC393C38EC382C2BE > 0xC390C2BBC2BEC391
 => TRUE
```

- When two strings start with similar prefixes then the integers may be equal
- Call strcoll to disambiguate these cases

What lies ahead? Hardware evolution driving major changes in algorithm choices:

- Quicksort to generate runs instead of Replacement Selection
  - Quicksort is cache oblivious and CPU cache is much more important in modern CPUs
  - As main memory grows the number of tapes we can handle increases proportionally and the number of runs decreases proportionally. So the number of merges decreases quadratically. It’s less important to use a heap to maximize the run length.

- Parallel Sort
  - Modern hardware is scaling by adding CPUs faster than by increasing clock speeds.
  - Infrastructure for parallel query is already committed and can be used for sorting.

- Using SIMD instructions (MMX/SSE/AVX)
  - Most operators limited to floats but recently more general purpose (integer) vector operations have been supported
  - Registers keep increasing in size -- the next generation of CPUs will have 512 byte registers which may be sufficient

- Using a GPU to sort using OpenCL or CUDA
  - Quicksort unsuitable -- Radixsort or Bitonic sort would be needed
  - https://wiki.postgresql.org/wiki/PGStrom