External Sorting

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Initial data and final results are both stored on disks.

- For large data set, two passes over data are the minimum.
- Algorithms typically consist of two phases:
  - The first phase produces a set of files containing half-processed data.
  - The second phase processes these files to produce a totally ordered permutation of the input data.
- Disk I/O bandwidth is often the performance bottleneck.
  - Most algorithms use only two passes.
  - Most algorithms try to balance the time between the two phases.
  - Most algorithms try to maximize overlap between I/O and internal sorting operations.

Two Algorithm Categories

- *Distribution-Based Sorting:*
  - The first phase partitions the input data into k disjoint, ordered buckets — each bucket contains numbers smaller than those in the next bucket.
  - In the second phase, each bucket is sorted independently.
- *Merge-Based Sorting:*
  - The first phase partitions the input data into (unordered) chunks of approximately equal size; sorts these chunks in main memory and writes the "runs" to disk.
  - The second phase merges the runs in main memory and writes the sorted output to the disk.

Jim Gray's External Sort Benchmarks

An annual competition to promote *practical* parallel sorting algorithms. Started in 1985 by Jim Gray. (`sortbenchmark.org`)

- Datamation (1985-2001) — Sort one million 100-byte records. (The *original* benchmark. Deprecated since the task became too easy.)
- MinuteSort (since 1994) — Sort as many records as possible in one minute.
- PennySort (1994-2011) — Sort as much as possible for a penny's worth of system time.
- TeraByteSort (1998-2008) — Sort ten billion 100-byte records. (Deprecated since it became too similar to MinuteSort.)
- JouleSort (since 2007) — Minimize the amount of energy required to sort 10^8 – 10^{12} records (10GB – 100TB).
- GraySort (since 2009) — Maximize the sort rate (TBs/minute) achieved while sorting a very large amount of data (currently 100TB minimum).

Datamation Benchmark

"Sort one million records (total 95MB data) from disk to disk."

- *Data format* — 10-byte key inside 100-byte record
- *System configuration* — unrestricted except no special design allowed.
- *Fact:* Can be achieved by a *single-pass* sort.

year	*name*	*system*	*#nodes*	*#disks*	*time(s)*
1986	–	Tandem (SMP)	2	2	3,600.0
1987	–	Tandem (SMP)	3	6	980.0
1988	–	Cray 1 (Vector)	1+	1	28.0
1993	AlphaSort	DEC Alpha SMP	1	16	9.1
1994	AlphaSort	DEC Alpha SMP	3	28	7.0
1996	Nsort	SGI SMP	12	96	4.2
1997	NowSort	SUN Sparc Cluster	32	64	2.4
1999	Millennium Sort	DELL NT Cluster	16x2	?	1.2
2000	Diaprism Sorter	HP Xeon Cluster	4	32	1.0
2001	NowSort	Intel P3 Cluster	32x2	32x5	0.44

In contrast, early parallel systems couldn't provide competitive results.

year	*system*	*#nodes*	*#disks*	*time(s)*
1990	Sequent (SMP)	8	4	83.0
1992	Intel iPSC/2 (DMS)	32	32	58.0

MinuteSort Benchmark

"Sort as much as possible in one minute."

year	*name*	*system*	*#nodes*	*#disks*	*GB*
1995	AlphaSort	DEC Alpha SMP	3	36	1.1
1997	Nsort	SGI SMP	32	?	3.5
1998	Nsort	SGI SMP	32	?	5.8
2000	Nsort	SGI SMP	32	?	12
2004	Nsort	Itanium2 Cluster	32	2,350	32
2006	NeoSort	Itanium2 Cluster	32	128	40
2007	TokuSampleSort	Disk Cluster	400x2	400x6	214
2009	Hadoop	Cluster	195x8	195x4	500
2012	Flat Datacenter Storage	Disk Cluster	256	1,033	1,401
2014	DeepSort	Xeon Cluster	384x2	384x8	3,700

Case Study: AlphaSort ('93-'95)

- *Hardware:* A SMP with commodity components
  - 1-3 DEC Alpha AXP 3000/7000 processors
  - 256MB memory (memory bus 640MB/s)
  - 10-28 disks (I/O bus 4 x 100MB/s)
- *Software:* DEC OpenVMS, threads over shared memory
  - Threads allow overlapping between I/O and computing
  - Locks are used to ensure proper access to shared data
- *Algorithm:* Quicksort
  - Focusing on overlapping I/O and computing
  - Small degree of parallelism — only 3 concurrent processes

Single-Node AlphaSort

1. Divide one million records into 30-50 groups; read them one by one from disk.
2. As each group becomes available, use a separate thread to quicksort it into a run.
3. Merge the runs using a replacement-selection tree.
4. Gather records into contiguous buffer and write to disk.

Key Optimizations:

- *Multiple threads* — overlapping I/O and internal sorting.
- *Disk striping* — to allow parallel reads and writes. (*Hardware:* 3 controllers and 28 disks; *Software:* a file striping layer)
- *Lots of memory* — 256-384MB for sorting 95MB data; this affords quicksort for internal sorting

Internal Quicksort Options

Each record is 100 bytes, with a 10-byte key:

key	data

Option 1. Sort records directly.

- An array of 100-byte records is quicksorted in place.
- Simple and straightforward; no additional memory is needed.

Option 2. Sort pointers.

- An array of 4-byte record pointers is generated and quicksorted.
- The records must be referenced during the sort to resolve each key comparison, but only the pointers are moved during the sort.

Internal Quicksort Options (cont.)

Option 3. Sort (key, pointer) pairs.

- An array of 16-byte (key, pointer) pairs is generated and quicksorted.
- The pointers are not dereferenced during the quicksort. This is known as a detached key sort.

Option 4. Sort (key-prefix, pointer) pairs.

- An array of 8-byte (key-prefix, pointer) pairs is generated and quicksorted.
- If two key-prefixes are equal, their pointers are dereferenced and the full keys are compared.
- Motivation for this approach is to fit more (key, pointer) pairs in cache and to align by cache-line.

Performance Comparison

Choice	Array-Gen	Quicksort	Output
records	–	20.47s	2.49s
pointers	0.08s	12.74s	3.52s
(key, pointer)'s	1.07s	4.02s	3.41s
(key-prefix, pointer)'s	0.84s	3.32s	3.41s

Parallel AlphaSort

1. Each thread requests affinity to a processor.
2. Master thread responsible for all file operations; worker threads do sorting and memory-intensive operations.
3. Master reads records; workers quicksort the data groups.
4. Master merges the runs; workers gather records into contiguous buffers.
5. Master writes sorted buffers to disk.

Performance Tuning: Balancing workload

- Time to read *vs.* Time to sort
- Time to merge *vs.* Time to gather records

Case Study: NowSort ('97-'01)

- *Hardware:* A cluster of commodity workstations
  - Up to 64 SUN ultraSPARC I workstations, each has 64-128MB memory and 2-4 SCSI disks
  - Connected with an Marinet switch (160MB/s)
- *Software:* GLUnix + N copies of Solaris
  - *Supports a simple parallel environment* — process start-up, job control, etc., but no dynamic scheduling
  - *Shared-nothing with explicit communication* — One process per node
  - *Active messages* — 10 μs latency, 35 MB/s bandwidth
- *Algorithm:* Quicksort + Bucket Sort
  - Input data is assumed to be drawn from an uniform distribution, and is evenly partitioned across processors' local disks.

Single-Node NowSort

1. Read all records into memory (no group partitioning).
2. Internally sort the records (several options available).
3. Gather records into contiguous buffer and write to disks.

Note: No threading is used — overlapping is achieved by other means, *i.e.* reading records directly into buckets.

Parallel NowSort

1. *Read* — Each processor reads records from its local disk into memory.
2. *Communicate* — Key values are examined and the records are sent to their destination buckets. (One of the buckets is local.)
3. *Sort* — Each processor sorts its local records.
4. *Write* — Each processor gathers and writes its records to local disk.

Main Issue: Hiding the overhead of communication.

Internal Sort Options

Option 1. Quicksort

- Quicksort the (key-prefix, pointer) pairs.

Option 2. Bucket Sort + Quicksort

- While reading records into memory, *simultaneously* examine the high-order b bits of the keys and place keys into the the appropriate buckets.
- Each bucket is sorted individually with quicksort.
- The number of buckets (hence the value of b) is determined such that the average number of keys per bucket fits into the L2 cache.
- Each bucket entry contains the most significant 32-bits of a key after the top b-bits, and a pointer to the the full record.

Internal Sort Options (cont.)

Option 3. Bucket Sort + Partial Radix-Sort

- Distribute keys into buckets as in the previous algorithm.
- But use a partial radix-sort instead of quicksort to sort each bucket.
- Two passes are performed over the keys, each with a radix size of 11 bits.
- Since the two passes together examine only 22-bits of (80-b)-bit keys, a final clean-up phase is performed, where keys with ties in the top 22-b bits are bubble-sorted.

Experimental data show that this last option has the best performance.

NowSort Optimizations

- User-level software striping.
- Use `mmap` instead of `read`, to avoid the system double-buffering problem.
- Use (key-prefix, pointer) pairs in internal sorting.
- Overlap I/O with CPU computation:
  - With the use of buckets, the need for this overlap is low.
- Overlapping I/O with communication:
  - *Interleaved* — A single thread alternates reading and communicating. Input data are saved in (small) send buffers, one for each destination. As soon as a buffer is full, its data is sent out. (Active message is a key for this to work.)
  - *Threaded* — One I/O thread and one communication thread.

Two-Pass NowSort

- *Create Runs* — The one-pass sort (*read*, *sort*, and *write*) is repeated to create multiple sorted runs on disk.

  Two threads are used:
  - A *reader* for reading records from disk, moving keys and pointers into buckets, and signaling when the buffer is full;
  - A *writer* for sorting each bucket, writing records to disk, and signaling when the buffer is empty.
- *Merge Runs* — The sorted runs are merged into a single sorted file.

  Three threads are used:
  - A *reader* for prefetching chunks from sorted runs;
  - A *merger* for performing merging and copying records into a write buffer;
  - And a *writer* for for writing the records to disk.

Other External Sorting Highlights

- *GpuTeraSort* ('06 Penny Benchmark) — Sorting with GPU co-processor with a bitomic sorting algorithm.
- *Hadoop Sort* ('09 Minute Benchmark) — Based on the "MapReduce" model. Essentially a bucket sort.