Lazy and Eager Approaches for the Set Cover Problem

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Abstract

The Set Cover problem is tantalizingly simple to describe: given a collection $F$ of sets, each containing a subset of a universe $U$ of objects, find a smallest sub-collection $A$ of $F$ such that every object in $U$ is included in at least one of the sets in $A$. However, like many such combinatorial problems, Set Cover is NP-hard, meaning that it is unlikely that an efficient algorithm will be found, and that approximation algorithms must be preferred for non-trivial problem instances. One well-known approximation approach for Set Cover is to repeatedly add the set with the most uncovered items to the solution, continuing until every element in the universe is covered; this Greedy approach has a provable logarithmic approximation ratio, essentially the best feasible ratio. Here we study the implementation of the Greedy approach to Set Cover, evaluating eager and lazy versions and other implementation options. Experiments with several large datasets demonstrate that lazy “as required” priority queue updates should be preferred, rather than eager “as soon as possible” ones; and that when implemented in this way, the Greedy mechanism can solve some large instances of the Set Cover problem very quickly. This practical superiority contrasts with the lazy version’s having a demonstrably higher worst-case operation cost.

Keywords: set cover, priority queue, lazy update, approximation algorithm.

1 Introduction

The Set Cover problem arises in a very broad range of logistic and layout problems, including monthly beer production, the roll-out schedule of a network, and data mining of a collection of sequenced DNA data for simple reduction, the roll-out schedule of a network, and data mining, including logistic and layout problems, including monthly beer production.

The challenge is to identify a smallest sub-collection of the smallest sets in $F$ such that every object in $U$ is included in at least one of the sets in $A$. That is, what is required is a smallest subset $A \subseteq F$ such that every home in $U$ appears in at least one set in $A$. If there is more than one minimal-size solution, secondary criteria could be used to choose between them. Other Set Cover scenarios include information retrieval, where a query over words (elements) computes the smallest sub-collection of documents, drawn from a large collection of documents, that as a whole contain all of the query words.

Like many such combinatorial problems, Set Cover is NP-hard. Consequently, to find optimal solutions, some exhaustive search component is required; hence, only trivially small problem instances can be solved exactly within reasonable resource bounds. Approximation techniques must then be used for large-scale problem instances. Any approximation technique is a compromise between solution effectiveness and implementation efficiency, with high effectiveness usually only possible at the cost of low efficiency. At one extreme in this spectrum, exhaustive methods generate optimally effective solutions, but typically require time that is exponential in the size of the problem instance; at the other extreme, taking (for the Set Cover problem) $A = F$ certainly guarantees coverage and is very fast to compute, but might be ineffective by a very large multiplicative factor. Between these extremes, a good approximation algorithm balances a guarantee on effectiveness (for example, in the case of Set Cover, through a proof that the solution generated by the approximation algorithm is at most some bounded factor larger than the size of an optimal solution) with desirable asymptotic execution analysis. For most NP-hard problems, the latter requirement corresponds to running time that is polynomial in the size of the problem instance.

The Greedy algorithm for Set Cover, introduced in detail in Section 2, can be measured against these criteria. The solutions it constructs are bounded relative to the size
of a corresponding optimal solution [6, 10], and it executes in polynomial time. It remains an important focus of study because it has provably the best approximation factor possible in polynomial time, is known to perform very well in practice across multiple kinds of instances and often generates solutions that are within 10% of optimum [7, 8]. Recent GREEDY variants include a disk-based version [4], and fast parallel algorithms [2, 3]; these options add to the versatility and usefulness of the approach.

The GREEDY algorithm proceeds by repeatedly adding to the solution the remaining set with the largest number of uncovered elements, seeking to obtain the greatest gain for each additional set that is used. To find the set with the greatest number of uncovered elements a priority queue data structure is employed to track the size of every candidate set. That structure is one of the focuses of this paper, as we consider in detail how to implement the GREEDY approach, and balance the costs of different types of queue update operations. One obvious option is to use a binary heap, but other – simpler – structures can also be used. A critical issue that affects the choice is the rate at which updates are performed – as each set is added to the growing solution, a large number of the other remaining sets might need to have their “uncovered element” counts decreased. In this EAGER-GREEDY implementation, the priority queue must always be able to quickly emit the next set to be added to the solution, meaning that many updates to set sizes might be required at each iteration.

To counter this possible inefficiency, we explore the use of lazy update options, in which changes to sets are deferred as long as possible and until they are actually necessary. The resultant implementation, LAZY-GREEDY, performs a different balance of elementary operations, and executes more quickly than the EAGER-GREEDY version on public datasets. Our experimental results indicate that LAZY-GREEDY outperforms the eager greedy method in terms of running time, and is also competitive against a recently described greedy bucket-based algorithm [4].

The notion of lazy evaluation can be further applied to the process of updating a set, that is, identifying in it (and removing from it) covered items. We explore this option too, terminating those operations as soon as it can be known that the set in question will not be the next one added to the solution.

The remainder of the paper is structured as follows. Section 2 explains the technical background of the SET COVER problem; shows how the GREEDY strategy computes solutions with a guaranteed approximation bound; and describes the EAGER-GREEDY implementation of that approach. Section 3 focuses on the bottleneck issue with EAGER-GREEDY, and describes an alternative lazy-update version of the same GREEDY paradigm. We also describe an input pattern that gives rise to a worst-case number of set updates. Section 4 describes the experiment environment and datasets used to evaluate the pool of SET COVER algorithms; and then demonstrates that the new lazy approach solves large instances of the problem significantly faster than does the eager implementation of the same procedure. The lazy implementation is also competitive against the more complex DF-GREEDY bucket-based implementation of the eager greedy procedure developed by Cormode et al. [4]. Extending the notion of “laziness” to the set difference operator is considered in Section 5. Section 6 then concludes our presentation.

Figure 1: An instance of the SET COVER problem over \( U = \{0, 9\} \), with \( F = \{S_0, \ldots, S_8\} \), and \( S_0 = \{0, 5, 6\} \), \( S_1 = \{1, 2, 6, 7\} \), \( S_2 = \{3, 8\} \), \( S_3 = \{4, 9\} \), \( S_4 = \{0, 1, 2, 3, 4\} \), and \( S_5 = \{7, 8, 9\} \).

2 The SET COVER Problem

We now state the SET COVER problem, and describe the best-known approximation algorithm for solving it.

2.1 Definition

The universe of objects under consideration is supposed, without loss of generality, to consist of the \( n \) integers \([0..n-1]\), where, as a general notation, \([0..z-1]\) stands for the set \( \{0, 1, \ldots, z-1\} \). An instance of the SET COVER problem relative to the universe \( U = \{0..n-1\} \) is given by a collection \( F \) of \( m \) sets \( \{S_0, \ldots, S_{m-1}\} \), with \( S_i \subseteq U \), and \( \bigcup_{i=0}^{m-1} S_i = U \). That is, it is known that every item in \( U \) appears in at least one of the sets \( S_i \) in \( F \).

The challenge then posed is to find a smallest sub-collection \( A \subseteq F \) such that \( \bigcup_{S \in A} S = U \). The size of the solution is given by \(|A|\). Another way of categorizing the cover size that we do not pursue in this paper is the total number of elements in the sets making up \( A \), that is, the objective is to minimize \( \sum_{S \in A} |S| \) subject to the constraint \( \bigcup_{S \in A} S = U \). It is convenient to describe the set \( A \) in terms of the indices of the sets that are being included in the solution. The interpretation of \( A \) to be used in a particular situation will always be clear from the context.

Figure 1 illustrates a simple instance of the SET COVER problem in which \( U = \{0, 9\} \) and \( F = \{S_0, \ldots, S_8\} \). It is also helpful to define a value \( M \) as the total of the \( m \) sets that are involved in a SET COVER instance, \( M = \sum_{S \in [0..m-1]} |S| \). In the example, \( M = 19 \), and is a measure of the size of the input required when describing the instance. The smallest solution for the instance in Figure 1 is \( A = \{0, 4, 5\} \), since these three sets cover \( U \), and there is no smaller sub-collection of \( F \) that also covers \( U \). The alternative sub-collection \( \{S_0, S_1, S_2, S_4\} \) also covers \( U \) and is free of redundancy (none of the sets can be removed without coverage being lost), but is not optimal.

The SET COVER problem is NP-hard [12]. Indeed, Feige [6] showed that, unless NP has “slightly super-polynomial time algorithms”, SET COVER cannot be approximated within a factor of \((1 - o(1)) \ln n \). The next section presents the GREEDY approach, whose approximation factor is very close to this bound.

2.2 The GREEDY Strategy

Algorithm 1 provides an overview of the GREEDY approximation mechanism for SET COVER. The idea behind it is very simple: at each iteration of the loop, the set with the largest number of uncovered items is identified, and added to a growing solution \( A \). That process is continued until every element in \( U \) is covered; the precondition
Algorithm 1 The Greedy approach

Input: Family $F$ of $m$ sets $S_i \subseteq U = \{0..n - 1\}$, and with $\bigcup_{i \in \{0..m - 1\}} S_i = U$.

Output: Set $A$ of indices of sets with $\bigcup_{i \in A} S_i = U$.

1: $A \leftarrow \{\}$
2: $\text{covered} \leftarrow \{\}$
3: while $\text{covered} \neq U$ do
4:   $i \leftarrow \arg\max_{j \in \{0..m - 1\}} \{ |S_j \setminus \text{covered}| \}$
5:   $A \leftarrow A \cup \{i\}$
6:   $\text{covered} \leftarrow \text{covered} \cup S_i$
7: end while
8: return $A$

Algorithm 2 The Eager-Greedy implementation

Input: As for Algorithm 1

Output: As for Algorithm 1

1: $A \leftarrow \{\}$
2: $\text{covered} \leftarrow \{\}$
3: $\text{pqueue} \leftarrow \{\}$
4: for $j \leftarrow 0$ to $m - 1$ do
5:   $\text{pqueue}.\text{insert}((|S_j|, j))$
6: end for

7: while $\text{covered} \neq U$ do
8:   for each set $S_i$ that contains $c$ do
9:     $\text{updates}[j] \leftarrow \text{updates}[j] \cup \{c\}$
10: end for
11: for all $j$ for which $\text{updates}[j] \neq \{\}$ do
12:     $\langle uc, i \rangle \leftarrow \text{pqueue}.\text{maximum}()$
13:     $A \leftarrow A \cup \{i\}$
14:     $\text{pqueue}.\text{delete}(\langle uc, i \rangle)$
15:     $S_j \leftarrow S_j \setminus \text{updates}[j]$
16:     $\text{pqueue}.\text{insert}(\langle uc - |\text{updates}[j]|, j \rangle)$
17:     $\text{updates}[j] \leftarrow \{\}$
18: end for
19: end for
20: while $\text{covered} \neq U$ do
21: end while
22: return $A$

Figure 2: The six sets of the Set Cover instance shown in Figure 1, sorted into increasing size order. The first set to be considered is $S_4$.

that $\bigcup_{i \in \{0..m - 1\}} S_i = U$ guarantees that the termination condition for the loop will be met.

Figure 2 shows the initial state of Algorithm 1, as applied to the problem instance shown in Figure 1. The Greedy approach first adds set $S_4$ to the solution, and in doing so, covers items $\{0, 1, 2, 3, 4\}$. The second set considered is then $S_5$, since it (now) has three uncovered items, more than the larger set $S_1$, which only has two uncovered items. Once $S_5$ is added to the solution $A$, there are only two uncovered items, $5$ and $6$, and $S_0$ covers both of them, whereas $S_1$ only covers one of them. With $S_0$ included in the solution, the main loop terminates; in this case, the optimal solution is identified.

Johnson [10] demonstrated that the Greedy approach constructs a solution that is not more than $1 + \ln n$ times larger than the minimal one; improved bounds were provided by Slavik [13]. Young [14] and Dutta [5] provide surveys of this development. The Greedy approach also performs well in practice, typically identifying solutions that are close to optimal [3, 4]. Extensions include parallel implementations designed for multi-processor architectures [2]; for disk-based operation [4]; enhancements that improve the worst-case approximation ratio [9]; and methods for on-line Set Cover problems [1].

2.3 Implementing Greedy: Eager Evaluation

Algorithm 1 leaves many details unspecified. Critical decisions that are required include:

- How to represent the sets $S_i$;
- How to manage the collection of sets so that the computation implied by the argmax evaluation at step 4 can be carried out; and
- How to represent the set covered so that the computations at steps 4 and 6 can be carried out.

Algorithm 2 shows one way in which these issues can be resolved. An explicit priority queue is introduced, with the usual operations assumed: insert(), to add a tuple $(uc, i)$ consisting of a set label $i$ and queue weight $uc$ (steps 5 and 20); maximum(), to remove and return the tuple with the largest weight $uc$ (step 9); and delete(), to locate and remove the tuple with the specified label $j$ (step 18). As well, details are given of the process to be followed when a set $S_i$ is added to the solution. The loop at step 11 iterates over the newly covered items in $S_i$, and removes each of them from the every other set $S_j$ in which it appears (step 13). Each such removal decreases the “uncovered symbol count” $uc$ of a set $S_j$, but these changes are all deferred until they can be processed in a batch at step 18, which locates that set in the priority queue, extracts its current $uc$ value, and then, at step 20, puts it back in the priority queue with a reduced $uc$ value. The batching process ensures that each $S_j$ that shares items with $S_i$ is updated just once per occurrence of step 9.

Two further details require elaboration. First, in order to identify at step 11 the items $c$ that are being newly covered, it is necessary for each element in $S_i$ to be checked for membership in $covered$. The most appropriate mechanism is for $covered$ to be stored as an indexed bitvector, with $covered[c]$ set to 1 if and only if $c \in covered$. Each lookup to $covered[c]$ requires $O(1)$ time; over all sets $S_i$, the cost is at most $\sum_{i \in \{0..m - 1\}} |S_i| = M$, that is, is linear in the size of the input description. Second, step 13 requires knowledge of the collection of sets $S_j$ that contain a given element $c$. An efficient way of supporting this need is to pre-compute an inverted index over the sets, so that a mapping is available from items to sets containing them [4]. Building an inverted index requires $O(M)$ time using distribution-sorting techniques, plus a corresponding amount of memory space to store it.
2.4 Priority Queue

With structures for covered and for identifying affected sets in place, the overall time required by EAGER-GREEDY is determined by the choice of priority queue structure: there are at most \(|F| = m|pqueue|\) operations required at step 9; and at most \(M\) decrease-weight operations required at steps 18–20. If the priority queue is implemented as a binary heap each operation requires \(O(\log m)\) time (since there are at most \(m\) sets in the heap); and the large number of update operations dominates the running time, giving rise to an \(O(M \log m)\) overall cost.

An obvious question is whether a binary heap is in fact the best choice. When a large number of decrease-weight operations must be balanced against a smaller number of extract-maximum operations, other options are also possible. The fact that all of the item weights manipulated in the priority queue are integers between 0 and \(n - 1\) also adds flexibility.

In particular, a simple array-plus-lists structure can be used as a priority queue. An array pqueue of \(n\) elements is maintained, with pqueue[\(uc\)] a list of the indices of the sets that currently have uc uncovered elements. A variable pqueue.top indicates the largest index in pqueue that is non-null; and after every extract-maximum operation, pqueue.top is updated via a sequential scan through pqueue looking for the next non-null entry. To carry out the decrease-weight operation at steps 18–20, the current entry in pqueue for set \(j\) is identified via a table indexed by set identifier; and that node is deleted from its current list pqueue[\(uc\)], then re-linked in to pqueue[\(uc\) − updates[\(j\)]] where updates[\(j\)] is the number of changes being made to \(S_j\). This takes \(O(1)\) time per set moved. In addition, an auxiliary stack records the values of \(j\) for which updates[\(j\)] is no-empty, to that the loops at step 17 does not introduce unnecessary overhead.

Allowing for the fact that the total cost of all of the scanning required as part of the extract-maximum operations is \(O(n)\), the execution time for EAGER-GREEDY is now \(O(n + M)\). Moreover, since the collection \(F\) covers \(U\), it must be that \(M \geq n\). Hence, with this queue structure, the EAGER-GREEDY approach described in Algorithm 2 executes in \(O(M)\) time.

3 A Lazy Implementation

Section 2.4 describes one way in which the small number of extract-maximum operations can be balanced against a much larger number of decrease-weight operations. But a significant imbalance remains between the number of extract-maximum operations and the number of decrease-weight operations, and it is interesting to ask if the overall envelope of operations can be decreased by explicitly trading a large drop in the number of decrease-weight operations for a smaller increase in the number of extract-maximum operations.

3.1 Deferred Cleaning

In Algorithm 2, each execution of step 9 returns the next largest set, according to the number of uncovered elements. Then, as that set is added to the solution, every other set that contains common uncovered elements is adjusted. Those adjustments ensure that the counts of uncovered elements for all sets are correct at all times.

Algorithm 3 The LAZY-GREEDY implementation

Input: As for Algorithm 1
Output: As for Algorithm 1
1. \(A \leftarrow \{\}\)
2. \(covered \leftarrow \{\}\)
3. \(pqueue \leftarrow \{\}\)
4. for \(j \leftarrow 0\) to \(m - 1\) do
5. \(\quad pqueue.\text{insert}(\langle |S_j|, |j| \rangle)
6. end for
7. while covered \(\neq U\) do
8. \(\quad \langle uc, i \rangle \leftarrow pqueue.\text{maximum}()\)
9. \(\quad S_i' \leftarrow S_i - covered\)
10. \(\quad\) if \(|S_i'| = |S_i|\) then \(\quad\) // all items in \(S_i\) were clean
11. \(\quad\) \(A \leftarrow A \cup \{i\}\)
12. \(\quad covered \leftarrow covered \cup S_i\)
13. \(\quad\) else \(\quad\) // some items in \(S_i\) were covered
14. \(\quad\) \(S_i \leftarrow S_i'\)
15. \(\quad pqueue.\text{insert}(\langle |S_i|, i \rangle)\)
16. end if
17. end while
18. return \(A\)

If those counts were not reduced so relentlessly, the putative sizes of the competing sets – the weights manipulated by the priority queue – would deviate from their true values. But they would always be upper bounds, and the worst that could happen is that a set might be emitted by the priority queue as being the next largest, only for a subsequent check to find that in fact it contained covered elements that had not yet been noted, and could not be included as part of the greedy solution just yet.

Algorithm 3 presents the revised process. Step 8 accesses the largest set in the priority queue, denoted as \(S_i\). In recognition of the fact that \(S_i\) might include one or more items covered in previous iterations, the first processing undertaken is a set difference \(S_i - \text{covered}\), in which each element of \(S_i\) is checked against the set \(covered\). If the set difference operation removes no elements from \(S_i\), then all elements were uncovered, and it can be added to the greedy solution (steps 11–12).

But if there were covered elements present in \(S_i\), it cannot be added to the solution, since it might not be the set containing the largest number of uncovered items – there might be another smaller set that has that claim. Instead, the cleaned set \(S_i'\) is retained, and is reinserted into the priority queue (step 15). The main loop then iterates, and the newly largest set is chosen as the next maximum. This process continues until a clean set containing only uncovered items emerges from the priority queue.

With the revised arrangement, the while loop at step 7 executes more than \(|A|\) times. But each reinsertion operation at step 15 should move the set \(S_i\) down by multiple slots in the priority queue ordering; that is, there might be fewer reinsertions in total, decreasing the total number of queue operations required.

3.2 Example

Consider the example instance shown in Figure 1. The initial state of the priority queue is as shown in Figure 2. The largest set, \(S_4\), is removed, and because no items have been covered yet, all of its elements are clean, and \(S_4\) is added to the solution. The next largest set is \(S_1\), with a putative uc of 4. But when \(S_1\) is checked for cleanliness, it is discovered that two of its elements (1 and 2) have become covered, and its uncovered size is actually only two. So a cleaned set \(S_1' = \{6, 7\}\) is added back into the
The ordering of the queue operations. In a problem in-
collection, marked by the various boxes; plus additional
iterations possible, that is, is there a limit on the number
of sets input to the problem. This observation gives rise to
3.3 Worst-Case Performance

When processed by LAZY-GREEDY, the input arrange-
ment shown in Figure 3 gives rise to a repetitive cycle of
computations. It first processes set $S_{m-1}$, finds that all of
its elements are clean, and hence covers them. It then cy-
cles through $S_{m-2}$, $S_{m-3}$ and so on down to $S_0$, cleaning
the same group of $m$ elements out of each. Once all $m-1$
remaining sets are clean, set $S_{m-2}$ returns to the head of
the queue in a fully uncovered state, and the cycle is re-
pet ed recursively, exactly as if a pathological instance of
$m-1$ sets had been input.

Since set $S_i$ cycles through the head of the priority
queue a total of $m-i$ times, the total number of execu-
tions of step 8 in Algorithm 3 is

$$\sum_{i=0}^{m-1} (m-i) = \frac{m(m+1)}{2} \approx \frac{m^2}{2}.$$

Hence, the number of extract-maximum operations per-
formed on the pathological input instances is $\Theta(M^{2/3})$,
and remains sub-linear in the size of the input description.
That asymptotic bound also applies to the number of times
that step 15 is executed.

The other place in the LAZY-GREEDY approach where
the number of iterations might be different from the
EAGER-GREEDY approach is at step 9. Each time a set $S_i$
reaches the head of the queue, every element $e$ in it is
checked against covered, taking $O(1)$ time per element.
Elements that have already been covered are removed as
they are discovered, and only the uncovered elements are
retained in the set $S_i$ that is reinserted into the queue. But
the elements that were not covered will be checked again
when $S_i$ reaches the head of the queue next time, and it
is no longer possible to bound the number of “check cov-
ered” operations by $M$. Indeed, for the pathological input
structure that is illustrated in Figure 3, the total number of
check-covered operations for an instance of size $m$, is
given by the summed size of the (recursive) problem inst-
ces from size $m$ down to size 1:

$$\sum_{i=1}^{m} i^3 + 2i^2 - i = \Theta(m^4).$$

The behavior of the pathological input arrangement can be
summarized thus:

**Observation 1.** There is a SET COVER problem in-
case of size $M$ that requires the LAZY-GREEDY method
to spend $\Theta(M^{4/3})$ time, including $\Theta(M^{2/3})$ extract-
maximum operations in the priority queue.

Note that this time bound is asymptotically greater than the
$O(M)$ time that is achieved by the EAGER-GREEDY
implementation. Fortunately, typical problem instances do
not display the particular structure required to force this
bad behavior, and when executed on typical instances, the
LAZY-GREEDY approach shows substantial benefits com-
pared to the EAGER-GREEDY implementation.

4 Experimental Results

We now demonstrate the difference that lazy evaluation
make on typical SET COVER problem instances.

4.1 Datasets and Experiment Environment

Three datasets are used in the experiments – RETAIL, AC-
CIDENTS and WEBDOCS – taken from the Frequent Item-
### 4.2 Implementations

Java implementations of EAGER-GREEDY and LAZY-GREEDY were prepared. All of the implementation executions were restricted to the usage of a single thread by default and had the runtime JIT (Just-In-Time) optimization enabled by default. All data structures were presumed to fit in to main memory. In the case of the EAGER-GREEDY implementation, the first operation carried out was to construct the index that is required, with that time included in the reported execution times.

The internal representations for the input sets and for covered were carefully chosen. A Boolean bit-vector of \( n/32 \) four-byte integers represents the set covered, allowing constant-time check-covered operations. Each of the sets was stored in an allocated segment out of an array of \( M \) integers, with covered elements rotated to the end of each set’s zone, and uncovered elements retained at the front of each zone. There was no resizing or de-fragging the underlying array.

The priority queue pqueue for tracking the set sizes was implemented as an array of size \( n \), in which each bucket was indexed by uc, and contained the identifier of the first set of that size, with other sets threaded from that first one. In the case of the EAGER-GREEDY mechanism, the priority queue lists were doubly-linked, and contained three fields: a next pointer, a prev pointer, and the uc value for that set, the latter being needed to allow the pqueue.delete\((j)\) operation to be efficient (step 18 in Algorithm 2). Double threading of list nodes was required, because the nodes being deleted might be anywhere in their list. Access to the \( j \)th set, required at the same step, is achieved in \( O(1) \) time by simply storing the set of priority queue nodes in a single large array (rather than as independently malloc’ed objects), with \( S_j \) stored in the \( j \)th array element. Each list was implemented as last-in first-out structure, with insertions always at the head.

In the LAZY-GREEDY approach a similar priority queue is maintained, but because deletions only occur as extract-maximum operations at the front of each list, no uc value is required, and single-threading suffices.

These various considerations lead to the space costs shown in Table 2. For the file WEBDOCS, the total nominal space requirement for the EAGER-GREEDY implementation was thus 2,355 MB; with 1,178 MB required for the LAZY-GREEDY implementation. That is, the index that is required for the EAGER-GREEDY approach essentially doubles the amount of memory space required. All of the values are stored as integer indices into either pqueue or into the array of sets. Naturally, if any of \( n, m, \) or \( M \) is greater than \( 2^{32} \), then eight-byte integers would be required rather than the four-byte ones assumed in these calculations.

### 4.3 Worst-Case Behavior

Table 3 shows execution times and operation counts for the EAGER-GREEDY and LAZY-GREEDY implementations when applied to the extreme problem instances described in Section 3.3. As anticipated by Observation 1, when \( m \) doubles, the number of extract-maximum operations required by LAZY-GREEDY increases by a factor of four, and both the number of check-covered operations required and the measured running time increase by a factor of sixteen. As \( m \) doubles, the input size \( M \) increases by a factor of roughly eight. For SET COVER instances that have this structure, the extra space required by the EAGER-GREEDY approach is a sound investment, and prevents super-linear (in \( M \)) execution times.
Table 4: Performance of \textit{EAGER} required to read each file (text format) is in Section 4.5. As currently implemented, the time reinsert operations for the three datasets. As anticipated, the \textit{EAGER} implementation performs a minimal number of extract-maximum operations, just one per set added to the solution $A$, whose size is at most $m$. But there is a very large number of queue reinsertion operations performed, close to $M$, and even with the array-based priority queue described in Section 2.4, each reinsertion is relatively costly, involving multiple tests for boundary cases and multiple pointer assignments.

4.5 Disk-Friendly Greedy

Cormode et al. [4] have also considered the question of how to implement the \textit{Greedy} method for \textit{Set Cover}. Their \textit{DF-Greedy} (disk-friendly greedy) approach is designed to minimize the number of non-sequential operations, and maximize the number of sequential operations over the data, and hence provides good performance when the input data is so voluminous that it cannot be stored in main memory. Cormode et al. introduce a fidelity param-

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{$m$} & \textbf{$M$} & \multicolumn{2}{c|}{\textbf{time (s)}} & \multicolumn{2}{c|}{\textbf{extract-maximum}} & \multicolumn{2}{c|}{\textbf{check-covered}} \\
\hline
 & & \textbf{E-G} & \textbf{L-G} & \textbf{E-G} & \textbf{L-G} & \textbf{E-G} & \textbf{L-G} \\
\hline
200 & 4,039,900 & 0.37 & 1.17 & 200 & 20,100 & 4,039,900 & 204,681,650 \\
300 & 13,589,850 & 1.28 & 5.65 & 300 & 45,150 & 13,589,850 & 1,028,283,725 \\
400 & 32,159,800 & 2.98 & 17.47 & 400 & 80,200 & 32,159,800 & 3,237,393,300 \\
\hline
\end{tabular}
\caption{Table 4: Execution time and operation counts \textit{LAZY-GREEDY} and \textit{EAGER-GREEDY} on pathological input sequences.}
\end{table}
eter $p > 1$ that permits further imprecision of the output size, in order to control the number of disk seek operations required. That is, the DF-GREEDY approach can be thought of as being an “approximate-approximation” mechanism, with a slightly weakened performance guarantee of $1 + p \ln n$ [4].

The DF-GREEDY implementation has much in common with the LAZY-GREEDY approach described here. The critical difference is that instead of the priority queue being indexed directly by current set size, as given the by $uc$ component of the tuple, it is instead indexed by $\lfloor \log_p n \rfloor$; that is, the number of distinct buckets in $pqueue$ is given by $\lfloor \log_p n \rfloor$. Each bucket is represented as a disk file containing explicit sets, and the only requirement for memory space in the on-disk version of DF-GREEDY is the $n/32$ words required for the covered bit-vector.

The main processing loop of the DF-GREEDY method works systematically through the sets in a given bucket, for example, the $k$th bucket containing sets of at least $p^k$ and less than $p^{k+1}$ elements. As each set is read from the corresponding file and processed, it is checked for cleanliness. Provided that a set is clean, or nearly clean – where nearly clean is defined as containing at least $p^k$ uncovered items – it is incorporated into the solution $A$. On the other hand, if, after cleaning, the set contains fewer than $p^k$ uncovered items, it is written back to disk by appending it to the file storing the corresponding range of set sizes, and held for later processing.

The use of a geometric sequence of sizes means that no set can be processed more than $\lfloor \log_p n \rfloor$ times, and hence that there are at most $n \log_p n$ read and write operations while the algorithm executes, and, summed across the geometric sequence of set sizes, at most $MP/(p-1)$ (that is, $O(M)$) words of data written. As many as $\log_p n$ files are required to be open for writing at any given instant, and one file for reading.

The final column of Table 4 shows the performance of an in-memory version of the DF-GREEDY approach. It is implemented using the same data structures as shown in Table 2, using a $pqueue$ with $\log_p n + 2n + O(1)$ words required, with set size $uc$ and a forward pointer required as part of each element. For the file WEBDOCS, for example, and with $p = 1.1$, there is a net space saving of around 14 MB compared to LAZY-GREEDY.

 Needless to say, the DF-GREEDY approach is also fast when implemented this way, since it has a very similar execution profile to the LAZY-GREEDY mechanism. Indeed, the only significant difference between them is that in the LAZY-GREEDY approach, each bucket in $pqueue$ represents a single set size, whereas in the in-memory DF-GREEDY implementation, each bucket represents a range of set sizes spanning (when $p = 1.1$) a 10% margin. That is, another way of categorizing the LAZY-GREEDY approach is that it is the limiting implementation, as $p \to 1$, of the in-memory DF-GREEDY mechanism.

The size of the solutions is very slightly higher when the in-memory DF-GREEDY is employed, but they are still close to the range established by the two “exact” approximate implementations. (Of course, the size of “true” solutions to these problem instances is not known.)

Interestingly, on the extreme problem instances described in Section 3.3, DF-GREEDY performs very well. For instance, with $m = 400$, DF-GREEDY with $p = 1.1$ requires just 0.35 seconds to return the solution, checking whether 70,391,613 items are covered. This is ten times faster than EAGER-GREEDY and over forty times faster than LAZY-GREEDY (Table 3). The point is that DF-GREEDY is not concerned when the set in focus has had a small fraction of its elements already covered, and in many cases adds the set to the solution anyway, bypassing the cascading cycle of cleansings that hinder the other two implementations.

Cormode et al. [4] compare in-memory and on-disk versions of their DF-GREEDY method with a range of other implementations, including an EAGER-GREEDY implementation. Using a 2.8 GHz MacOS machine with 8 GB of main memory, their in-memory DF-GREEDY requires 93 seconds to process WEBDOCS with $p = 1.001$, and around 70 seconds with $p = 1.1$, compared to an EAGER-GREEDY execution time of 199 seconds. One possible explanation for the variation in execution time between their implementation of DF-GREEDY and our implementation of DF-GREEDY (shown as requiring 5 seconds in Table 4) is the use of different data structures; another contributing factor may be different experimental assumptions (for example, we do not include data reading times in Table 4).

5 Partial Set Cleansing

One further avenue was explored, still with the objective of reducing the execution time. Table 4 shows that the LAZY-GREEDY approach requires a minimum of three times more check-covered operations than does EAGER-GREEDY. Much of that effort is spent removing covered items from dirty sets even after it is known that set will not be the next one added to the solution. Removal of covered elements is, of itself, not wasted effort. But checking of the uncovered elements embedded in the same set is in some sense unhelpful, since those uncovered elements will all get checked again the next time this set emerges from the priority queue.

The idea of partial set cleansing is to interrupt the processing of checking a set once some threshold of “dirtiness” is exceeded, knowing that it will be some time before this set emerges again from the queue, and knowing that in the intervening period, more of the elements might have become covered.

Two different strategies were explored. The first was to abandon cleansing set $S_i$ as soon as enough covered items had been identified in it to confirm that it could not be the next one added into the solution. That is, if set $S_i$ was from $pqueue[uc]$, and the next largest set was in (say) $pqueue[uc']$, then as soon as $uc - uc' + 1$ covered items have been found in $S_i$, it is returned to the queue in bucket $pqueue[uc' - 1]$, and attention switched to the set or sets in bucket $pqueue[uc']$.

To avoid repeatedly testing and retesting elements from the start of each set, a variable restart point is added to each node in the queue, to record the position from which check-covered operations should resume, when and if this set returns to the front of the queue again. Resuming the next loop of check-covered operations from restart point rather than the beginning of the set increases the likelihood of identifying covered items; but does not remove the need for every item in the set to be checked before it can be added to the solution.

The second strategy was to continue checking set elements until some fixed fraction of the set was found to be covered, and reinsert a partially cleansed set into the queue as soon as that condition was met. When set cleansing is resumed, it is again from a stored restart point.
Table 5 shows the costs associated with the revised process. Each approach to partial cleansing is able to slightly decrease the number of check-covered operations, but not by enough to also decrease the running time. Indeed, the number of extract-maximum operations grows significantly, adding considerably to the execution cost. It may be that other variants of this idea can be identified that achieve the hoped-for blend of attributes, but to date we have not identified a method that is significantly faster than the LAZY-GREEDY and DF-GREEDY implementations.

6 Conclusion and Future Work

We have explored the GREEDY approach to the SET COVER problem, describing and measuring the performance of a new implementation, the LAZY-GREEDY approach. Compared to the standard EAGER-GREEDY mechanism, the LAZY-GREEDY implementation requires around half the memory space, and as little as 5% of the execution time when applied to typical large problem instances. The trade-off is that the lazy set update process increases the worst-case running time to $\Omega(M^{4/3})$, compared to $O(M)$ for EAGER-GREEDY, where $M$ is the total size of the input.

The LAZY-GREEDY implementation can be viewed as a special-case in-memory version of the DF-GREEDY method of Cormode et al. [4]. An interesting question is whether that relationship can be exploited in some way, perhaps to combine the speed of the DF-GREEDY method with the solution performance bound enjoyed by the LAZY-GREEDY approach in a single sequentially-processing implementation that is oblivious as to whether its data is resident in memory or on disk, and also retain the worst-case usefulness of DF-GREEDY.

We are also intrigued by the observation, arising from our experiments, that tie-breaking in the GREEDY mechanism can lead to solutions of differing quality. As a further part of our ongoing study, we plan to explore randomized choice evaluation to determine if hill-descending approaches might be effective in practice. The idea here would be to specify a total execution time that may be spent, and then execute GREEDY as many times as possible within that time, in order to obtain in aggregate a better solution than is likely to arise from a single execution.

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References


