Brief Announcement: A greedy 2 approximation for the active time problem

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ABSTRACT
In this note, we give a very simple 2 approximation for the active time problem - we are given a set of pre-emptible jobs, each with an integral release time, deadline and required processing length. The jobs need to be scheduled on a machine that can process at most \( g \) distinct job units at any given integral time slot in such a way that we minimize the time the machine is on i.e. the active time. Our algorithm matches the state of the art bound obtained by a significantly more involved LP rounding scheme.

CCS CONCEPTS
• Theory of computation → Scheduling algorithms;

1 INTRODUCTION
In this paper, we consider the problem of scheduling jobs on a machine while minimizing the total time that the machine is on. This is captured by the active time model.

Active Time Model: We have a set of \( n \) jobs say \( J = \{1, 2, ..., n\} \) where each job \( j \) has a processing time \( p_j \) and must be scheduled in a window defined by a release time \( r_j \) and deadline \( d_j \) (\( p_j, r_j, d_j \) are integers). Jobs are pre-emptible at integral points within their window. Time is divided into integral units. We are given a single machine that can process at most \( g \) distinct job units in parallel. The machine is considered on i.e. active in a particular time unit when it is processing at least one job in that time unit. Our goal is to feasibly schedule the jobs in \( J \) while minimizing the active time (i.e. the number of time units that the machine is on).

Chang et al. [2] solve the problem exactly when jobs all have unit length. They show that the problem is NP hard when a job can have multiple disjoint windows but the complexity of the case where each job has a single contiguous window is unknown. The unit length version of this problem has been considered in other contexts such as in scheduling jobs with precedence constraints [6], finding a minimum b-clique cover in an interval graph [1], and rectangle stabbing [4].

The general problem with arbitrary integral job lengths was considered by Chang et al. [3] where the authors show that a minimal feasible solution is a 3-approximation. The authors also describe a significantly more complicated 2-approximation based on LP rounding which is the current best known upper bound for the problem.

The main result in this paper is a simple combinatorial algorithm which achieves a 2-approximation for the active time problem, matching the upper bound obtained by the LP rounding scheme described by Chang et al. [3].

2 PRELIMINARIES
A job \( j \) is said to be live at slot \( t \) if \( t \in [r_j, d_j] \). A slot is open if a job can be scheduled in it. It is closed otherwise. An open slot is full if there are \( g \) jobs assigned to it. It is non-full otherwise.

A feasible solution is given by a set of open time slots into which the jobs can be feasibly scheduled. Given a set of slots, we can find a feasible assignment of jobs or determine that no such schedule is possible by performing a simple flow computation (described in the appendix).

3 GREEDY ALGORITHM
All time slots are assumed to be open initially. Consider time slots from left to right. At a given time slot, close the slot and check if a feasible schedule exists in the open slots. If so, leave the slot closed, otherwise, open it again. Continue to the next slot.

THEOREM 3.1. The greedy algorithm described above gives a 2 approximation to the active time problem.

The remainder of this section is devoted to proving Theorem 3.1. We will bound the number of full and non-full slots separately. Let \( S \) and \( S^* \) denote the final greedy and optimal schedules respectively. Let \( |S| \) and \( |S^*| \) denote the number of open slots in \( S \) and \( S^* \) respectively. We first shift the job units in \( S \) as much as possible while maintaining feasibility. This is captured by the following lemma.

LEMMA 3.1. For any job \( j \) in time slot \( t \), \( j \) must be present in every non-full slot in the window of \( j \) earlier than \( t \) i.e. in the interval \([r_j, t]\).

Proof. The proof follows from left shifting. For any non-full slot \( t' \) earlier than \( t \) in the window of job \( j \), a unit of \( j \) must be present in \( t' \) since otherwise we would have left
shifted the unit from $t$ into $t'$ (this would be feasible since $t'$ is in $j$’s window and non-full). \hfill \Box

For the proofs of the remaining lemmas and the definitions of $a$, $b$, $a^*$ and $b^*$, we assume that all job units have been left shifted as much as possible in $S$. Let $b_t[j]$ and $b^*_t[j]$ denote the number of units of any job $j \in J$ scheduled by $S$ and $S^*$ respectively at or before $t$ i.e in time interval $[r_j,t]$. Let $a_t[j]$ and $a^*_t[j]$ denote the amount of job $j$ scheduled by $S$ and $S^*$ respectively in the time interval $[t,d_j]$. So, $b_t[j] + a^*_{t+1}[j] = b^*_t[j] + a_{t+1}^*[j] = p_j$. Let $T$ be the latest deadline of all the jobs.

**Lemma 3.2.** For any non-full slot $t$ opened by $S$, there must exist at least one job $j$ scheduled by $S$ in $t$ such that $b^*_t[j] \geq b_t[j]$.

**Proof.** If possible, suppose $b^*_t[j] < b_t[j]$ for all $j$ scheduled by $S$ in $t$ (as depicted in Figure 1). While moving left to right in our greedy algorithm, we would encounter $t$. At this point, by definition, we have already scheduled $b_t[j]$ of each job in $[1,t]$. We still need to schedule $a^*_{t+1}[j]$ of each job in the interval $[t+1,T]$.

Now, if we were to close $t$, then we would need to feasibly schedule the following in the interval $[t+1,T]$:

1. $a^*_{t+1}[j] + 1$ units$^1$ of each $j$ scheduled by $S$ in $t$.

By our assumption, since $b^*_t[j] < b_t[j]$ we have $a^*_{t+1}[j] > a_{t+1}[j]$ and so $a^*_{t+1}[j] + 1 \geq a_{t+1}[j]$.

2. $a^*_{t+1}[j]$ units of each $j$ live at $t$ but not scheduled by $S$ in $t$.

Since $j$ is not scheduled in $t$, all units of $j$ must have been scheduled by $S$ earlier than $t$ since otherwise we could have left shifted $j$ into $t$ as it is non-full$^2$.

Therefore, $b_t[j] = p_t$ and $a_{t+1}[j] = 0$. So $a_{t+1}[j] \leq a^*_{t+1}[j]$.

3. $a^*_{t+1}[j]$ units of each $j$ with $r_j > t$.

Clearly $a^*_{t+1}[j] = p_t = a^*_{t+1}[j]$. So $a_{t+1}[j] = a^*_{t+1}[j]$.

It can be seen that the mass of each job $j$ that ALG would need to schedule in $[t+1,T]$ (either $a^*_{t+1}[j]$ or $a_{t+1}[j] + 1$ units) is less than or equal to the mass of that job that OPT feasibly schedules in that interval ($a^*_{t+1}[j]$ units). When moving from left to right in our algorithm, when we reached $t$, all the slots in $[t+1,T]$ were open to schedule jobs. This means that, had we closed $t$ in $S$, we would still have been able to find a feasible schedule of the remaining job units in $[t+1,T]$, since OPT could find an optimal schedule for them in $[t+1,T]$. Therefore, we would have closed $t$ greedily while constructing $S$. Since we did not, our original assumption must have been incorrect. \hfill \Box

**Lemma 3.3.** The number of non-full slots in $S$ cannot exceed $|S^*|$.\hfill \Box

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**Proof.** Start at the right most non-full slot in $S$, say $t$. From Lemma 3.2, we can find one job $j$ in $t$ such that $b^*_t[j] \geq b_t[j]$. By Lemma 3.1, $j$ must be present in every non-full slot in $[r_j,t]$. This means that the number of non-full slots in $[r_j,t]$ cannot exceed $b_t[j]$ ($\leq b^*_t[j]$). So we can charge every non-full slot of $S$ in $[r_j,t]$ to a distinct slot in $S^*$ in $[r_j,t]$. Now, move to the latest non-full slot opened by $S$ strictly earlier than $r_j$ and repeat this process. In this way, we can charge every non-full slot in $S$ to distinct slots in $S^*$.

**Lemma 3.4.** The number of full slots in $S$ cannot exceed $|S^*|$.\hfill \Box

**Proof.** Let the number of full slots in $S$ be $|S_f|$. Since the maximum amount of job mass in any slot is $g$, the amount of job mass present in $S_f$ is $g|S_f|$. Similarly, the total job mass OPT scheduled is at most $g|S^*|$. By the conservation of job mass, $g|S_f| \leq g|S^*|$ and the lemma follows.

The total cost of our schedule is the sum of the full and non-full slots, and therefore, from Lemmas 3.3 and 3.4, this sum cannot exceed $2|S^*|$. This proves Theorem 3.1.

4 CONCLUSION

In this paper, we prove that a simple greedy algorithm matches the best known approximation ratio for the active time problem.

Crucially, the complexity status of this problem is still open as is breaking the 2 upper bound barrier. A possible avenue to achieving this is via a local search technique which we briefly sketch in the appendix.
A.1 Verifying a feasible schedule exists

Define a graph $G$ with vertex set consisting of one node for every job $j$, one node for every open time slot $t$ and a source and destination node ($s$ and $d$ respectively). Add edges from $s$ to each job node $j$ with capacity $p_j$. Add edges from each open time slot node $t$ to $d$ with capacity $g$. For each job $j$, for any time slot $t$ in its window, add an edge from job node $j$ to time slot node $t$ with unit capacity. The graph structure is shown in Figure 2. An active time instance has a feasible schedule on the set of open time slots if the maximum flow from $s$ to $d$ has value $\sum_{j \in J} p_j$. Furthermore, if a feasible schedule is possible, the unit capacity edges with non-zero flow give the mapping of job units to time slots.

A.2 Tight Example

The tight example consists of the following set of jobs - one job of length $g$ with window $[1, 2g]$, $g$ unit length jobs with window $[1, g+1]$ and $g - 1$ rigid jobs of length $g$ with window $[2, g+1]$. OPT would have opened time slot $t = 1$, scheduled all unit jobs there and therefore been able to schedule the $g$ length job above the rigid jobs. This gives a total cost of $g + 1$. However, our greedy algorithm closes time slot $t = 1$ since that is still feasible. Therefore, the unit jobs are forced to be scheduled above the rigid job, thereby pushing the long job out. This gives a total cost of $2g$. Thus, we get a lower bound of $\frac{2g}{g+1}$ which equals 2 as $g$ becomes large. The two schedules are depicted in Figure 3 (reprinted from [5]).

A.3 Local Search

A possible approach to breaking the 2 barrier for this problem is local search. Local search parametrized by a constant $b$ involves repeatedly performing local optimizations of the form - close $b$ open slots and open at most $b - 1$ new slots. We believe that this could provide a PTAS for this problem. Indeed, the best lower bound we currently have for local search is $1 + 1/(b-1)$. This is illustrated in Figure 4 (reprinted from [5]). Here, each column has $g - (g - 1)/b$ job mass in it (where $g$ is the capacity of the time slot) so that if we take any $b$ columns, the total job mass amounts to $(b - 1)g + 1$ which clearly cannot be scheduled in at most $b - 1$ slots. This gives a lower bound of $g/(g - (g - 1)/b)$ which tends to $1 + 1/(b-1)$ as $g$ becomes very large.

REFERENCES