Greedy Algorithms

Lecture 13
October 10, 2015
Part I

Greedy Algorithms: Tools and Techniques
What is a Greedy Algorithm?

No real consensus on a universal definition.

Greedy algorithms:
1. make decision incrementally in small steps without backtracking
2. decision at each step is based on improving local or current state in a myopic fashion without paying attention to the global situation
3. decisions often based on some fixed and simple priority rules
No real consensus on a universal definition.
What is a Greedy Algorithm?

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2. decision at each step is based on improving *local or current* state in a myopic fashion without paying attention to the *global* situation
3. decisions often based on some fixed and simple *priority* rules
Pros and Cons of Greedy Algorithms

Pros:

1. Usually (too) easy to design greedy algorithms
2. Easy to implement and often run fast since they are simple
3. Several important cases where they are effective/optimal
4. Lead to a first-cut heuristic when problem not well understood

Cons:

1. Very often greedy algorithms don’t work. Easy to lull oneself into believing they work
2. Many greedy algorithms possible for a problem and no structured way to find effective ones
3. CS 374: Every greedy algorithm needs a proof of correctness
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Greedy Algorithm Types

Crude classification:

1. **Non-adaptive**: fix some ordering of decisions a priori and stick with the order

2. **Adaptive**: make decisions adaptively but greedily/locally at each step
Greedy Algorithm Types

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1. **Non-adaptive**: fix some ordering of decisions a priori and stick with the order
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Plan:

1. See several examples
2. Pick up some proof techniques
Part II

Scheduling Jobs to Minimize Average Waiting Time
The Problem

- $n$ jobs $J_1, J_2, \ldots, J_n$. $J_i$ has non-negative processing time $p_i$
- One server/machine/person available to process jobs.
- Schedule/order the jobs to minimize total or average waiting time
- Waiting time of $J_i$ in schedule $\sigma$: sum of processing times of all jobs scheduled before $J_i$

<table>
<thead>
<tr>
<th></th>
<th>$J_1$</th>
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<th>$J_4$</th>
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<tr>
<td><strong>time</strong></td>
<td>3</td>
<td>4</td>
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<td>8</td>
<td>2</td>
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Waiting time of $J_i$ in schedule $\sigma$: sum of processing times of all jobs scheduled before $J_i$

Example: schedule is $J_1, J_2, J_3, J_4, J_5, J_6$. Total waiting time is

$$0 + 3 + (3 + 4) + (3 + 4 + 1) + (3 + 4 + 1 + 8) + \ldots =$$
The Problem

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\[
\begin{array}{ccccccc}
 & J_1 & J_2 & J_3 & J_4 & J_5 & J_6 \\
\text{time} & 3 & 4 & 1 & 8 & 2 & 6 \\
\end{array}
\]

Example: schedule is \( J_1, J_2, J_3, J_4, J_5, J_6 \). Total waiting time is

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Optimal schedule:
The Problem

- \( n \) jobs \( J_1, J_2, \ldots, J_n \). \( J_i \) has non-negative processing time \( p_i \)
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Example: schedule is \( J_1, J_2, J_3, J_4, J_5, J_6 \). Total waiting time is

\[
0 + 3 + (3 + 4) + (3 + 4 + 1) + (3 + 4 + 1 + 8) + \ldots =
\]

Optimal schedule: Shortest Job First. \( J_3, J_5, J_1, J_2, J_6, J_4 \).
Optimality of SJF

**Theorem**

*Shortest Job First gives an optimum schedule for the problem of minimizing total waiting time.*
Optimality of SJF

**Theorem**

*Shortest Job First gives an optimum schedule for the problem of minimizing total waiting time.*

**Proof strategy:** exchange argument
Optimality of SJF

**Theorem**

*Shortest Job First gives an optimum schedule for the problem of minimizing total waiting time.*

**Proof strategy:** exchange argument

Assume without loss of generality that job sorted in increasing order of processing time and hence \( p_1 \leq p_2 \leq \ldots \leq p_n \) and SJF order is \( J_1, J_2, \ldots, J_n \).
A schedule $J_{i_1}, J_{i_2}, \ldots, J_{i_n}$ is said to have an inversion if there are jobs $J_a$ and $J_b$ such that $S$ schedules $J_a$ before $J_b$, but $p_a > p_b$. 

Claim

If a schedule has an inversion then there is an inversion between two adjacently scheduled jobs.

Proof: exercise.
Inversions

Definition
A schedule $J_{i_1}, J_{i_2}, \ldots, J_{i_n}$ is said to have an inversion if there are jobs $J_a$ and $J_b$ such that $S$ schedules $J_a$ before $J_b$, but $p_a > p_b$.

Claim

If a schedule has an inversion then there is an inversion between two adjacently scheduled jobs.

Proof: exercise.
Proof of optimality of SJF

Recall SJF order is $J_1, J_2, \ldots, J_n$.

- Let $J_{i_1}, J_{i_2}, \ldots, J_{i_n}$ be an optimum schedule with fewest inversions.
- If schedule has no inversions then it is identical to SJF schedule and we are done.
- Otherwise there is an $1 \leq \ell < n$ such that $i_\ell > i_{\ell+1}$ since schedule has inversion among two adjacently scheduled jobs.
Proof of optimality of SJF

Recall SJF order is \( J_1, J_2, \ldots, J_n \).

- Let \( J_{i_1}, J_{i_2}, \ldots, J_{i_n} \) be an optimum schedule with fewest inversions.

- If schedule has no inversions then it is identical to SJF schedule and we are done.

- Otherwise there is an \( 1 \leq \ell < n \) such that \( i_\ell > i_{\ell+1} \) since schedule has inversion among two adjacently scheduled jobs.

Claim

The schedule obtained from \( J_{i_1}, J_{i_2}, \ldots, J_{i_n} \) by exchanging/swapping positions of jobs \( J_{i_\ell} \) and \( J_{i_{\ell+1}} \) is also optimal and has one fewer inversion.

Assuming claim we obtain a contradiction and hence optimum schedule with fewest inversions must be the SJF schedule.
Proof of Claim

\[ S \]

\[ i \]

\[ i_{l+1} \]

\[ S' \]

\[ i_{l+1} \]

\[ i \]

Change in waiting time

\[ = (t + t + p_{i,l+1}) - (t + t + p_{i,l}) \]

\[ = p_{i,l+1} - p_{i,l} \leq 0 \]
Part III

Scheduling to Minimize Lateness
Scheduling to Minimize Lateness

1. Given jobs $J_1, J_2, \ldots, J_n$ with deadlines and processing times to be scheduled on a single resource.

2. If a job $i$ starts at time $s_i$ then it will finish at time $f_i = s_i + t_i$, where $t_i$ is its processing time. $d_i$: deadline.

3. The lateness of a job is $l_i = \max(0, f_i - d_i)$.

4. Schedule all jobs such that $L = \max l_i$ is minimized.
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</tr>
</thead>
<tbody>
<tr>
<td>$t_i$</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>$d_i$</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

$l_1 = 2$ \hspace{2cm} $l_5 = 0$ \hspace{2cm} $l_4 = 6$
Initially $R$ is the set of all requests

```plaintext
curr_time = 0
max_lateness = 0
while $R$ is not empty do
    choose $i \in R$
    curr_time = curr_time + $t_i$
    if (curr_time > $d_i$) then
        max_lateness = max(curr_time − $d_i$, max_lateness)

return max_lateness
```

Main task: Decide the order in which to process jobs in $R$
Greedy Template

Initially $R$ is the set of all requests

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curr_time = 0
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return max_lateness

Main task: Decide the order in which to process jobs in $R$
Three Algorithms

1. Shortest job first — sort according to $t_i$.
2. Shortest slack first — sort according to $d_i - t_i$.
3. EDF = Earliest deadline first — sort according to $d_i$.

$t_1 = 1 \quad d_1 = 3$

$t_2 = 10 \quad d_2 = 12$
Three Algorithms

1. Shortest job first — sort according to $t_i$.
2. Shortest slack first — sort according to $d_i - t_i$.
3. EDF = Earliest deadline first — sort according to $d_i$.

Counter examples for first two: exercise
Theorem

Greedy with EDF rule minimizes maximum lateness.

Proof via an exchange argument.

Idle time: time during which machine is not working.
Theorem

*Greedy with EDF rule minimizes maximum lateness.*

Proof via an exchange argument.
Earliest Deadline First

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Idle time: time during which machine is not working.
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Theorem

*Greedy with EDF rule minimizes maximum lateness.*

Proof via an exchange argument.

Idle time: time during which machine is not working.

Lemma

*If there is a feasible schedule then there is one with no idle time before all jobs are finished.*
Assume jobs are sorted such that \( d_1 \leq d_2 \leq \ldots \leq d_n \). Hence EDF schedules them in this order.

**Definition**

A schedule \( S \) is said to have an inversion if there are jobs \( i \) and \( j \) such that \( S \) schedules \( i \) before \( j \), but \( d_i > d_j \).
Assume jobs are sorted such that $d_1 \leq d_2 \leq \ldots \leq d_n$. Hence EDF schedules them in this order.

**Definition**

A schedule $S$ is said to have an inversion if there are jobs $i$ and $j$ such that $S$ schedules $i$ before $j$, but $d_i > d_j$.

**Claim**

*If a schedule $S$ has an inversion then there is an inversion between two adjacently scheduled jobs.*

Proof: exercise.
Proof sketch of Optimality of EDP

- Let \( S \) be an optimum schedule with smallest number of inversions.
- If \( S \) has no inversions then this is same as EDF and we are done.
- Else \( S \) has two adjacent jobs \( i \) and \( j \) with \( d_i > d_j \).
- Swap positions of \( i \) and \( j \) to obtain a new schedule \( S' \)

Claim

Maximum lateness of \( S' \) is no more than that of \( S \). And \( S' \) has strictly fewer inversions than \( S \).
Part IV

Maximum Weight Subset of Elements: Cardinality and Beyond
Picking k elements to maximize total weight

1. Given \( n \) items each with non-negative weights/profits and integer \( 1 \leq k \leq n \).

2. Goal: pick \( k \) elements to maximize total weight of items picked.

<table>
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<tr>
<th></th>
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</tr>
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<tbody>
<tr>
<td><strong>weight</strong></td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
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\( k = 2 \): 
\( k = 3 \): 
\( k = 4 \):
Greedy Template

\[ N \text{ is the set of all elements } X \leftarrow \emptyset \]

(* \( X \) will store all the elements that will be picked *)

\[ \text{while } |X| < k \text{ and } N \text{ is not empty do} \]

\[ \text{choose } e_j \in N \text{ of maximum weight} \]

\[ \text{add } e_j \text{ to } X \]

\[ \text{remove } e_j \text{ from } N \]

\[ \text{return the set } X \]

**Remark:** One can rephrase algorithm simply as sorting elements in decreasing weight order and picking the top \( k \) elements but the above template generalizes to other settings a bit more easily.
N is the set of all elements X ← ∅
(* X will store all the elements that will be picked *)
while |X| < k and N is not empty do
    choose e_j ∈ N of maximum weight
    add e_j to X
    remove e_j from N
return the set X

Remark: One can rephrase algorithm simply as sorting elements in decreasing weight order and picking the top k elements but the above template generalizes to other settings a bit more easily.

Theorem
Greedy is optimal for picking k elements of maximum weight.
A more interesting problem

1. Given \( n \) items \( N = \{e_1, e_2, \ldots, e_n\} \). Each item \( e_i \) has a non-negative weight \( w_i \).

2. Items partitioned into \( h \) sets \( N_1, N_2, \ldots, N_h \). Think of each item having one of \( h \) colors.

3. Given integers \( k_1, k_2, \ldots, k_h \) and another integer \( k \)

4. Goal: pick \( k \) elements such that no more than \( k_i \) from \( N_i \) to maximize total weight of items picked.

\[
\begin{array}{cccccccc}
e & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & e_7 \\
weight & 3 & 2 & 1 & 4 & 3 & 2 & 1 \\
\end{array}
\]

\( N_1 = \{e_1, e_2, e_3\} \), \( N_2 = \{e_4, e_5\} \), \( N_3 = \{e_6, e_7\} \)

\( k = 5, k_1 = 2, k_2 = 2, k_3 = 2 \)
Greedy Template

\[ N \text{ is the set of all elements } X \leftarrow \emptyset \]
\[ (* X \text{ will store all the elements that will be picked } *) \]

while \( N \) is not empty do

\[ N' = \{ e_i \in N \mid X \cup \{e_i\} \text{ is feasible} \} \]

If \( N' \leftarrow \emptyset \) break

choose \( e_j \in N' \) of maximum weight

add \( e_j \) to \( X \)

remove \( e_j \) from \( N \)

return the set \( X \)
Greedy Template

\[ N \text{ is the set of all elements } X \leftarrow \emptyset \]
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If \( N' \leftarrow \emptyset \) break

choose \( e_j \in N' \) of maximum weight

add \( e_j \) to \( X \)

remove \( e_j \) from \( N \)

return the set \( X \)

Theorem

*Greedy is optimal for the problem on previous slide.*

Proof: exercise after class.

Special case of the general phenomenon of Greedy working for maximum weight independent set in a matroid. Beyond scope of
Part V

Interval Scheduling
Interval Scheduling

Problem (Interval Scheduling)

**Input:** A set of jobs with start and finish times to be scheduled on a resource (example: classes and class rooms).

**Goal:** Schedule as many jobs as possible
Problem (Interval Scheduling)

**Input:** A set of jobs with start and finish times to be scheduled on a resource (example: classes and class rooms).

**Goal:** Schedule as many jobs as possible

Two jobs with overlapping intervals cannot both be scheduled!
Greedy Template

\( R \) is the set of all requests
\( X \leftarrow \emptyset \) (* \( X \) will store all the jobs that will be scheduled *)

\textbf{while} \( R \) is not empty \textbf{do}

\hspace{1em} choose \( i \in R \)

\hspace{1em} add \( i \) to \( X \)

\hspace{1em} remove from \( R \) all requests that overlap with \( i \)

\textbf{return} the set \( X \)
Greedy Template

$R$ is the set of all requests
$X \leftarrow \emptyset$ (* $X$ will store all the jobs that will be scheduled *)

while $R$ is not empty do

choose $i \in R$

add $i$ to $X$

remove from $R$ all requests that overlap with $i$

return the set $X$

Main task: Decide the order in which to process requests in $R$
Earliest Start Time

Process jobs in the order of their starting times, beginning with those that start earliest.
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Figure: Counter example for earliest start time
Earliest Start Time

Process jobs in the order of their starting times, beginning with those that start earliest.

Figure: Counter example for earliest start time
Earliest Start Time

Process jobs in the order of their starting times, beginning with those that start earliest.

Figure: Counter example for earliest start time
Smallest Processing Time

Process jobs in the order of processing time, starting with jobs that require the shortest processing.
Smallest Processing Time

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Figure: Counter example for smallest processing time
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Figure: Counter example for smallest processing time
Smallest Processing Time

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Figure: Counter example for smallest processing time
Fewest Conflicts

Process jobs in that have the fewest “conflicts” first.
Fewest Conflicts

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**Figure**: Counter example for fewest conflicts
Fewest Conflicts

Process jobs in that have the fewest “conflicts” first.

Figure: Counter example for fewest conflicts
Fewest Conflicts

Process jobs in that have the fewest “conflicts” first.

Figure: Counter example for fewest conflicts
Earliest Finish Time

Process jobs in the order of their finishing times, beginning with those that finish earliest.
Earliest Finish Time

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Earliest Finish Time

Process jobs in the order of their finishing times, beginning with those that finish earliest.

[Diagram showing job durations arranged from left to right with the earliest finish time highlighted]
Earliest Finish Time

Process jobs in the order of their finishing times, beginning with those that finish earliest.

\[ \text{Diagram showing job durations} \]
Process jobs in the order of their finishing times, beginning with those that finish earliest.
The greedy algorithm that picks jobs in the order of their finishing times is optimal.
Correctness: Clearly the algorithm returns a set of jobs that does not have any conflicts
Proving Optimality

1. **Correctness**: Clearly the algorithm returns a set of jobs that does not have any conflicts.

2. For a set of requests $R$, let $O$ be an optimal set and let $X$ be the set returned by the greedy algorithm. Then $O = X$?
Proving Optimality

1. **Correctness:** Clearly the algorithm returns a set of jobs that does not have any conflicts.

2. For a set of requests $R$, let $O$ be an optimal set and let $X$ be the set returned by the greedy algorithm. Then $O = X$? Not likely!
Correctness: Clearly the algorithm returns a set of jobs that does not have any conflicts

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Proving Optimality

1. **Correctness:** Clearly the algorithm returns a set of jobs that does not have any conflicts.

2. For a set of requests $\mathbf{R}$, let $\mathbf{O}$ be an optimal set and let $\mathbf{X}$ be the set returned by the greedy algorithm. Then $\mathbf{O} = \mathbf{X}$? Not likely!
1. **Correctness:** Clearly the algorithm returns a set of jobs that does not have any conflicts.

2. For a set of requests $R$, let $O$ be an optimal set and let $X$ be the set returned by the greedy algorithm. Then $O = X$? Not likely!

Instead we will show that $|O| = |X|$
Proof of Optimality: Key Lemma

Lemma

Let $i_1$ be first interval picked by Greedy. There exists an optimum solution that contains $i_1$.

Proof.

Let $O$ be an arbitrary optimum solution. If $i_1 \in O$ we are done.

Claim: If $i_1 \notin O$ then there is exactly one interval $j_1 \in O$ that conflicts with $i_1$. (proof later)

Form a new set $O'$ by removing $j_1$ from $O$ and adding $i_1$, that is $O' = (O - \{j_1\}) \cup \{i_1\}$.

From claim, $O'$ is a feasible solution (no conflicts).

Since $|O'| = |O|$, $O'$ is also an optimum solution and it contains $i_1$. 
**Proof of Optimality: Key Lemma**

**Lemma**

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**Proof.**

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Proof of Optimality: Key Lemma

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**Proof.**

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**Claim:** If $i_1 \not\in O$ then there is exactly one interval $j_1 \in O$ that conflicts with $i_1$. (proof later)

1. Form a new set $O'$ by removing $j_1$ from $O$ and adding $i_1$, that is $O' = (O \setminus \{j_1\}) \cup \{i_1\}$.
2. From claim, $O'$ is a feasible solution (no conflicts).
3. Since $|O'| = |O|$, $O'$ is also an optimum solution and it contains $i_1$. □
Proof of Claim

Claim

If $i_1 \not\in O$, there is exactly one interval $j_1 \in O$ that conflicts with $i_1$.

Proof.

1. If no $j \in O$ conflicts with $i_1$ then $O$ is not optimal!
2. Suppose $j_1, j_2 \in O$ such that $j_1 \neq j_2$ and both $j_1$ and $j_2$ conflict with $i_1$.
3. Since $i_1$ has earliest finish time, $j_1$ and $i_1$ overlap at $f(i_1)$.
4. For same reason $j_2$ also overlaps with $i_1$ at $f(i_1)$.
5. Implies that $j_1, j_2$ overlap at $f(i_1)$ but intervals in $O$ cannot overlap.

See figure in next slide.
Figure : Since $i_1$ has the earliest finish time, any interval that conflicts with it does so at $f(i_1)$. This implies $j_1$ and $j_2$ conflict.
Proof of Optimality of Earliest Finish Time First

Proof by Induction on number of intervals.

**Base Case:** \( n = 1 \). Trivial since Greedy picks one interval.

**Induction Step:** Assume theorem holds for \( i < n \).

Let \( I \) be an instance with \( n \) intervals

\[ I' := I \text{ with } i_1 \text{ and all intervals that overlap with } i_1 \text{ removed} \]

**\( G(I), G(I') \):** Solution produced by Greedy on \( I \) and \( I' \)

From Lemma, there is an optimum solution \( O \) to \( I \) and \( i_1 \in O \).

Let \( O' = O - \{i_1\} \). \( O' \) is a solution to \( I' \).

\[
|G(I)| = 1 + |G(I')| \quad \text{(from Greedy description)} \\
\geq 1 + |O'| \quad \text{(By induction, } G(I') \text{ is optimum for } I' \text{)} \\
= |O|
\]
Implementation and Running Time

Initially $R$ is the set of all requests

$X \leftarrow \emptyset$ (* $X$ stores the jobs that will be scheduled *)

while $R$ is not empty

    choose $i \in R$ such that finishing time of $i$ is least

    if $i$ does not overlap with requests in $X$

    add $i$ to $X$

    remove $i$ from $R$

return the set $X$

- Presort all requests based on finishing time. $O(n \log n)$ time
- Now choosing least finishing time is $O(1)$
- Keep track of the finishing time of the last request added to $A$. Then check if starting time of $i$ later than that
- Thus, checking non-overlapping is $O(1)$
- Total time $O(n \log n + n) = O(n \log n)$
1. Interesting Exercise: smallest interval first picks at least half the optimum number of intervals.

2. All requests need not be known at the beginning. Such online algorithms are a subject of research.
Weighted Interval Scheduling

Suppose we are given $n$ jobs. Each job $i$ has a start time $s_i$, a finish time $f_i$, and a weight $w_i$. We would like to find a set $S$ of compatible jobs whose total weight is maximized. Which of the following greedy algorithms finds the optimum schedule?

(A) Earliest start time first.
(B) Earliest finish time first.
(C) Highest weight first.
(D) None of the above.
(E) IDK.

Weighted problem can be solved via dynamic programming. See notes.

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Greedy Analysis: Overview

1. **Greedy’s first step leads to an optimum solution.** Show that there is an optimum solution leading from the first step of Greedy and then use induction. Example, Interval Scheduling.

2. **Greedy algorithm stays ahead.** Show that after each step the solution of the greedy algorithm is at least as good as the solution of any other algorithm. Example, Interval scheduling.

3. **Structural property of solution.** Observe some structural bound of every solution to the problem, and show that greedy algorithm achieves this bound. Example, Interval Partitioning (see Kleinberg-Tardos book).

4. **Exchange argument.** Gradually transform any optimal solution to the one produced by the greedy algorithm, without hurting its optimality. Example, Minimizing lateness.
Takeaway Points

1. Greedy algorithms come naturally but often are incorrect. A proof of correctness is an absolute necessity.

2. *Exchange* arguments are often the key proof ingredient. Focus on why the first step of the algorithm is correct: need to show that there is an optimum/correct solution with the first step of the algorithm.

3. Thinking about correctness is also a good way to figure out which of the many greedy strategies is likely to work.