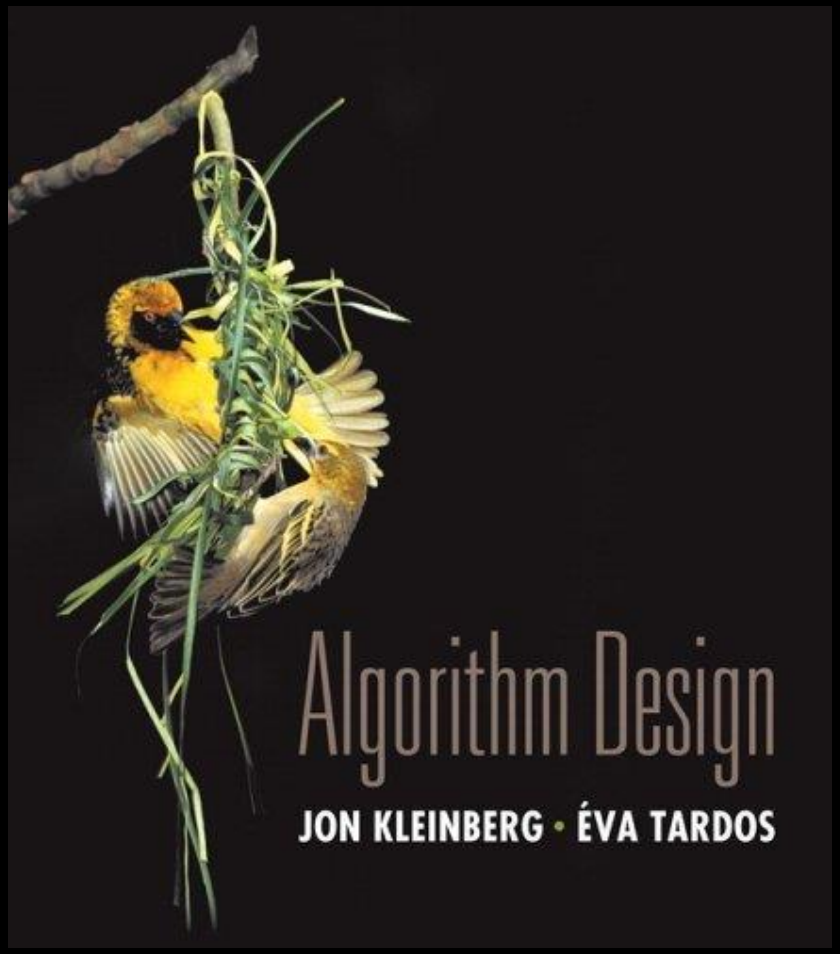


Chapter 4

Greedy Algorithms

Greedy Algorithms

General greedy algorithms. Consider the items in a specific order, makes "greedy" decisions

Pro: Typically very simple to implement and very efficient

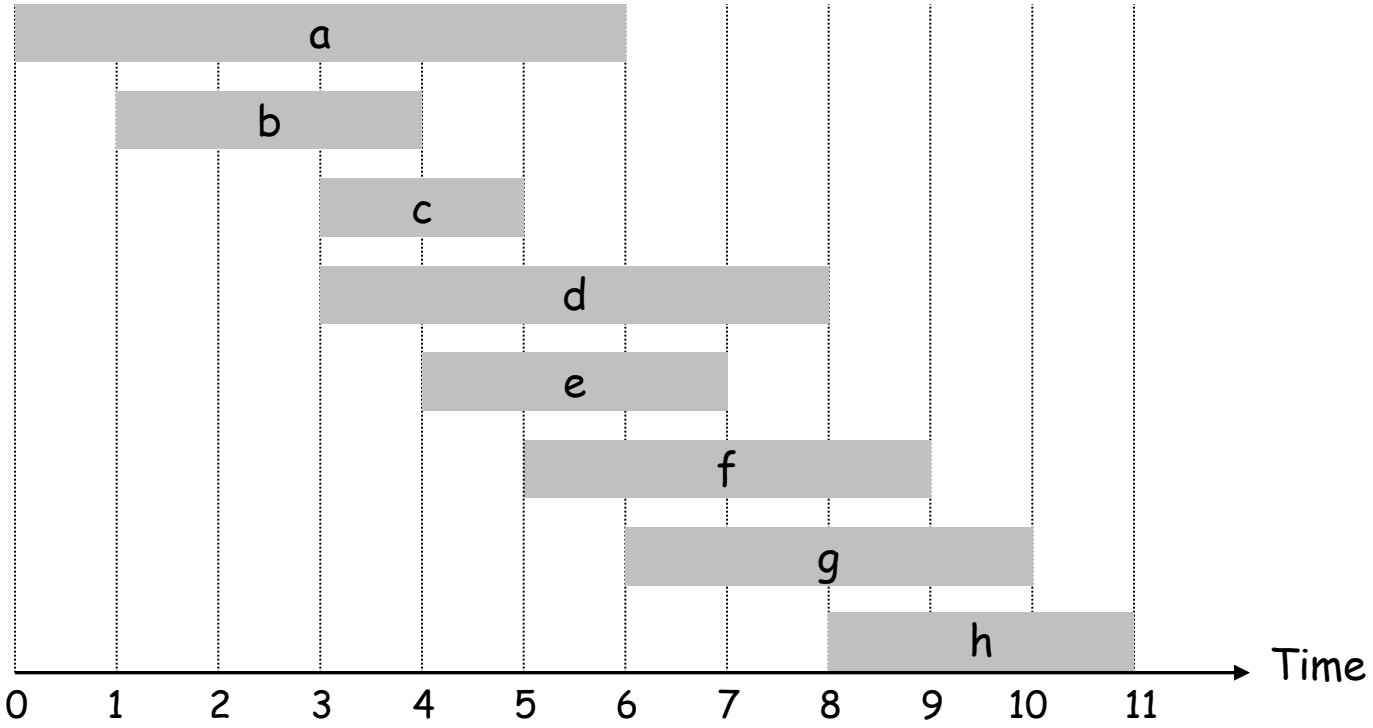
Con: Cannot solve every problem using a greedy algorithm, need to guarantee it works

4.1 Interval Scheduling

Interval Scheduling

Interval scheduling.

- Job j starts at s_j and finishes at f_j.
- Two jobs compatible if they don't overlap.
- Goal: find maximum subset of mutually compatible jobs.



Interval Scheduling: Greedy Algorithms

Greedy template. Consider jobs in some order. Take each job provided it's compatible with the ones already taken.

- [Earliest start time] Consider jobs in ascending order of start time s_j.
- [Earliest finish time] Consider jobs in ascending order of finish time f_j.
- [Shortest interval] Consider jobs in ascending order of interval length $f_j - s_j$.
- [Fewest conflicts] For each job, count the number of conflicting jobs c_j. Schedule in ascending order of conflicts c_j.

Interval Scheduling: Greedy Algorithms

Greedy template. Consider jobs in some order. Take each job provided it's compatible with the ones already taken.

breaks earliest start time

breaks shortest interval

breaks fewest conflicts

Interval Scheduling: Greedy Algorithm

Greedy algorithm. Consider jobs in increasing order of finish time. Take each job provided it's compatible with the ones already taken.

```
Sort jobs by finish times so that f_1 ≤ f_2 ≤ ... ≤ f_n.

A ← φ                                   ← jobs selected
for j = 1 to n {
   if (job j compatible with A)
      A ← A ∪ {j}
}
return A
```

Implementation.

- Remember job j* that was added last to A.
- Just need to check compatibility with last job: Job j is compatible with A if $s_j \geq f_{j^*}$.

Interval Scheduling: Greedy Algorithm

Greedy algorithm. Consider jobs in increasing order of finish time. Take each job provided it's compatible with the ones already taken.

```
Sort jobs by finish times so that f_1 ≤ f_2 ≤ ... ≤ f_n.

jobs selected
A ← φ
for j = 1 to n {
   if (job j compatible with A)
      A ← A ∪ {j}
}
return A
```

Implementation. $O(n \log n)$.

- Remember job j^* that was added last to A.
- Just need to check compatibility with last job: Job j is compatible with A if $s_j \geq f_{j^*}$.

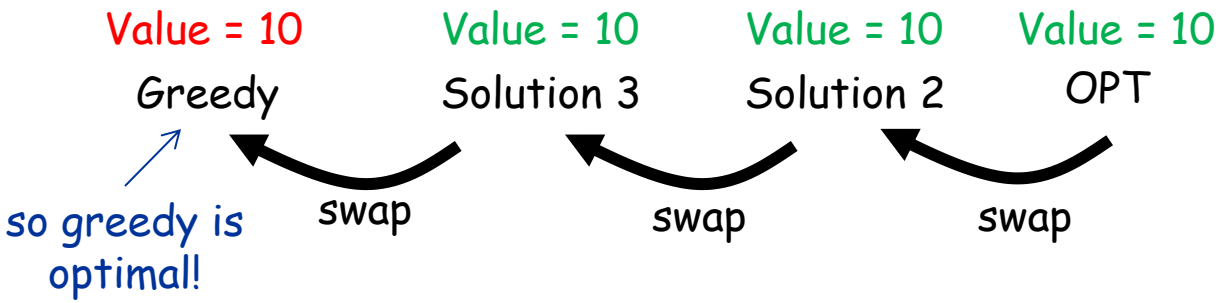
Interval Scheduling: Analysis

Need to argue that greedy returns an optimal solution

We will use the swapping argument, used to analyze most greedy algorithms

Swap Argument

- Replace one action of OPT for one action of Greedy, and show value does not get worse
- Repeating we bring OPT "closer and closer" until we reach Greedy

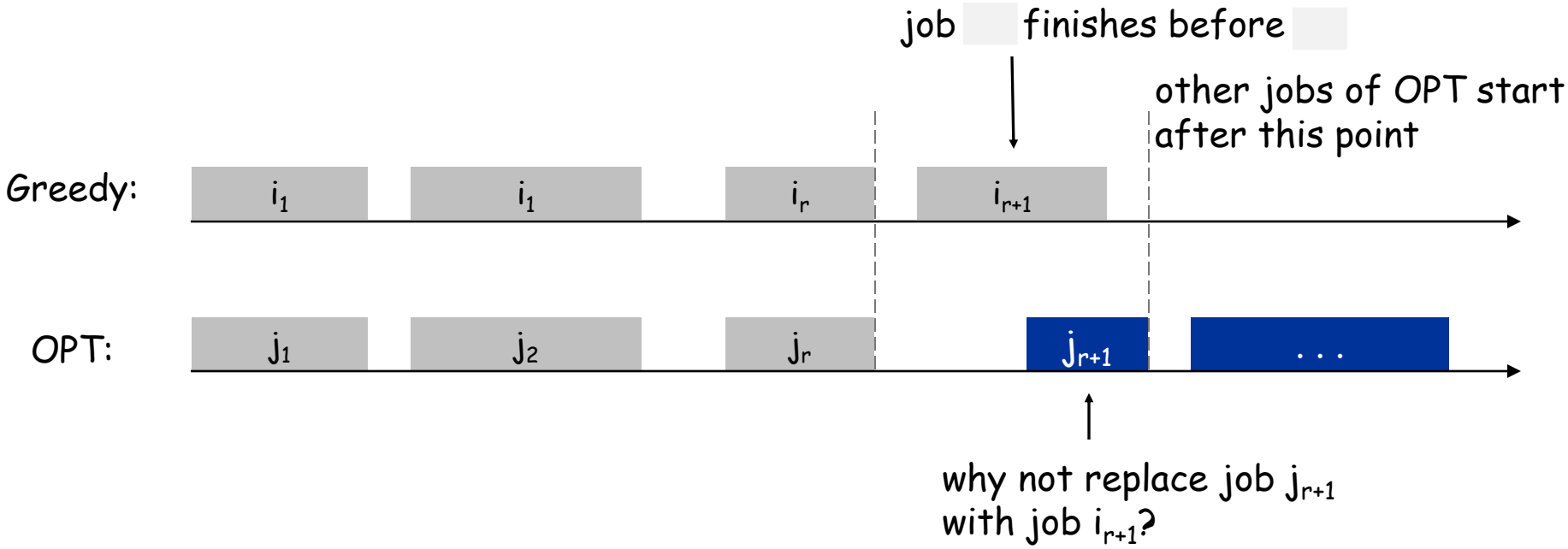


Interval Scheduling: Analysis

Theorem. Greedy on finish time algorithm is optimal.

Pf.

- Let $i_1, i_2, \ldots i_k$ denote set of jobs selected by greedy, sorted by finish
- Let $j_1, j_2, \ldots j_m$ denote the set of jobs of any optimal solution
- If this optimal solution equals the greedy one, we are done
- Suppose they are different. Look at first difference



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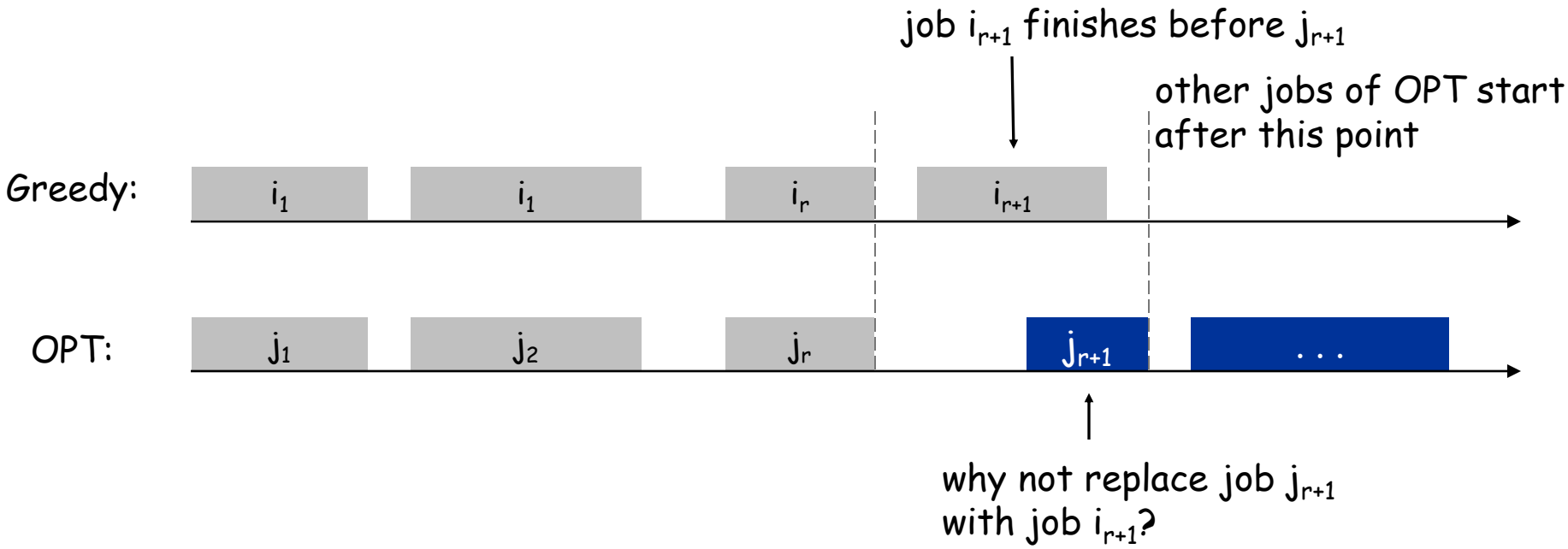

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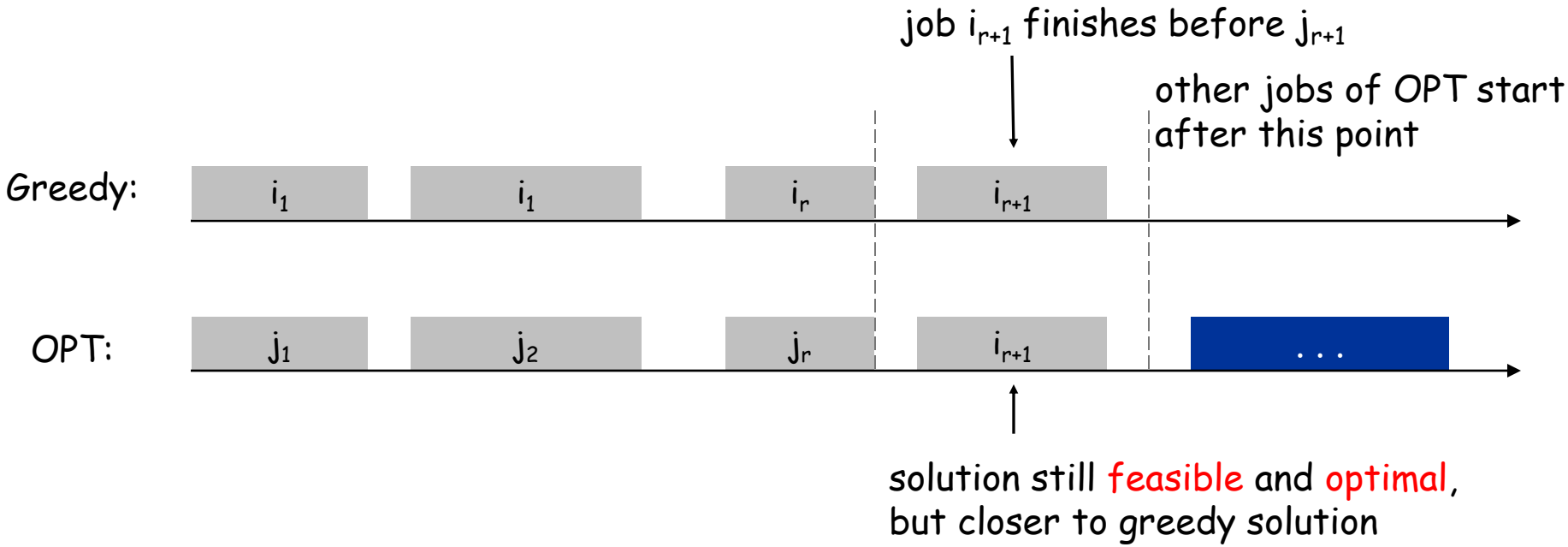

Interval Scheduling: Analysis

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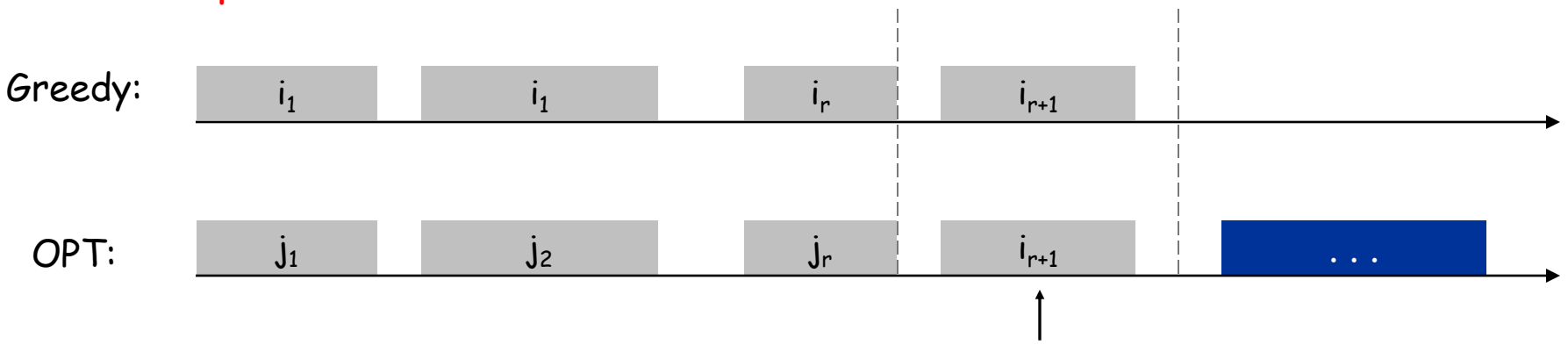
- Let $j_1, j_2, \ldots j_m$ denote the set of jobs of any optimal solution
- If this optimal solution equals the greedy one, we are done
- Suppose they are different. Look at first difference
- Swap!
- Repeating swap we reach greedy sol. with same optimal value => greedy is optimal

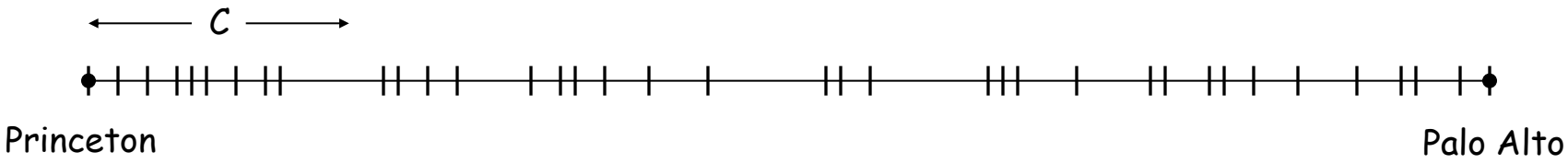


Example: Selecting fueling points

Selecting fueling points

Selecting fueling points.

- Road trip from Princeton to Palo Alto along fixed route.
- There are refueling stations at certain points along the way.
- Fuel capacity = C.
- Goal: Choose smallest number of refueling stops that make the trip possible



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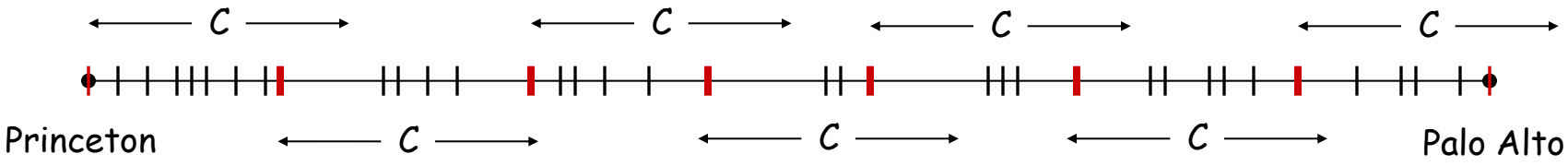
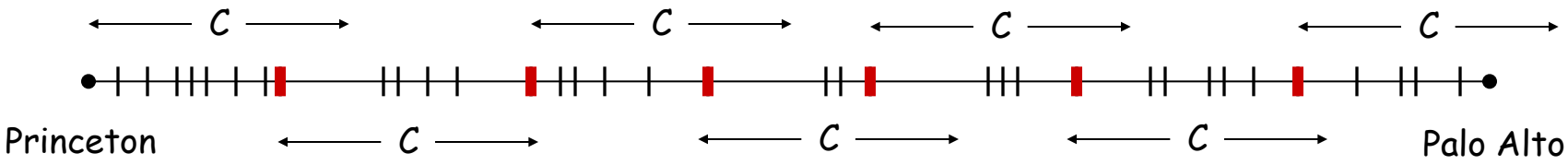


Task: Design a greedy algorithm for this problem, and give a brief argument for why it returns an optimal solution

Selecting fueling points

Solution: Go as far as you can before refueling.



To argue it returns an optimal solution, think "where could it go wrong/where is another algorithm smater"?

Maybe another algorithm could stop before it is required

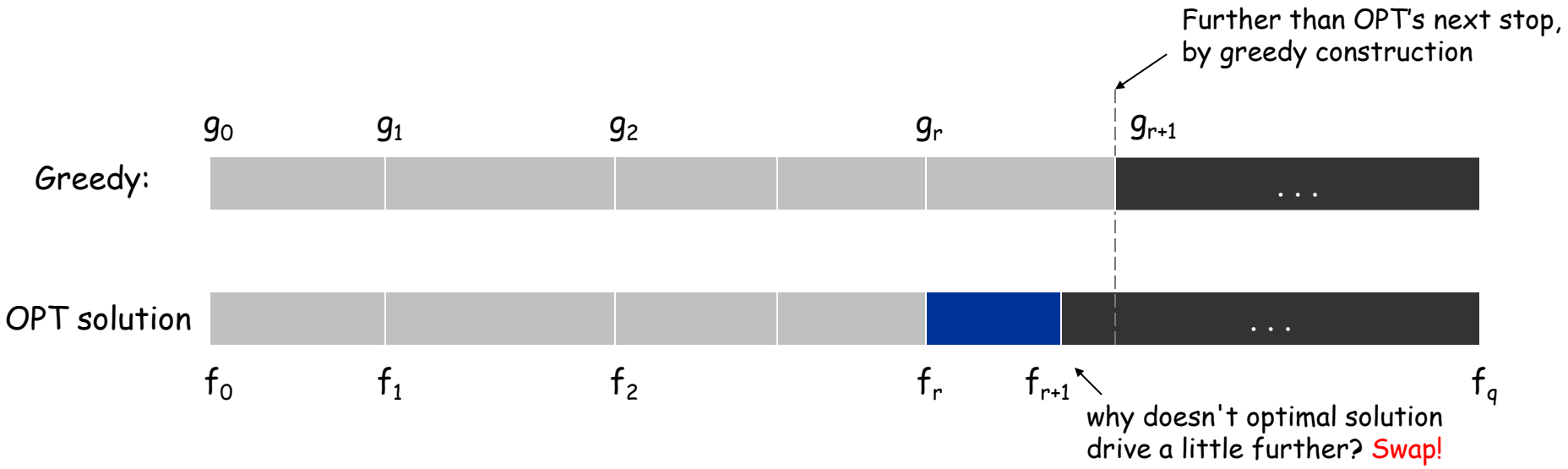
But that does not seem to help...

Selecting Breakpoints: Correctness

Theorem. Greedy algorithm is optimal.

Pf. (Swap argument)

- Consider optimal solution. Suppose different from greedy solution (otherwise we are done)
- Look at first time solutions differ

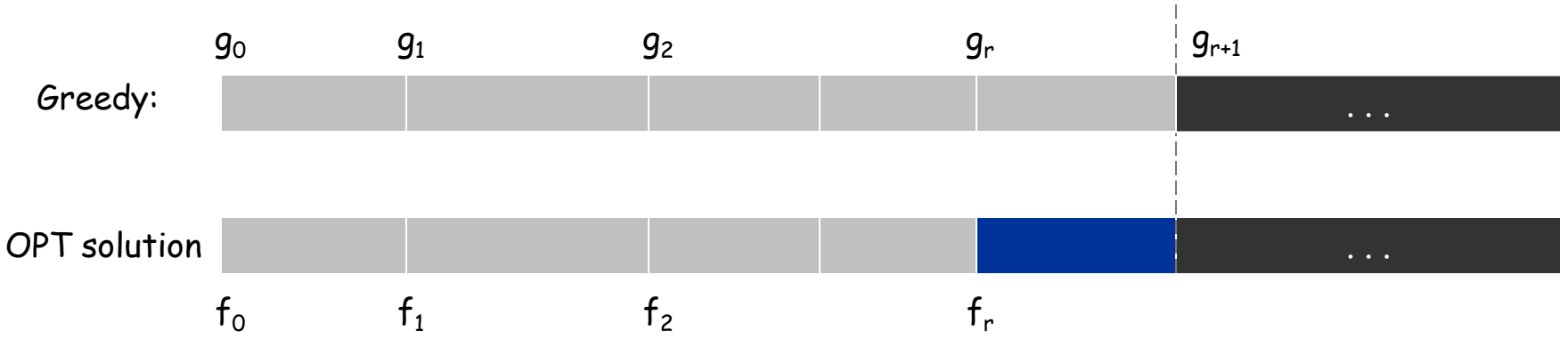


Selecting Breakpoints: Correctness

Theorem. Greedy algorithm is optimal.

Pf. (Swap argument)

- Consider optimal solution. Suppose different from greedy solution (otherwise we are done)
- Look at first time solutions differ
- Swap to make solution more similar to greedy solution with same value (number of stops)
- Repeat to reach greedy sol. with same value => greedy is optimal



Scheduling to Minimize Lateness

Scheduling to Minimizing Lateness

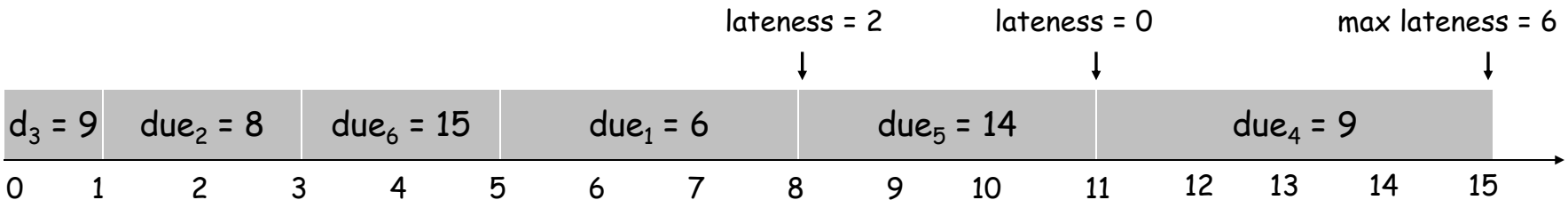
Minimizing lateness problem.

- Machine processes one job at a time.
- Job j requires $time_j$ units of processing time and is due at time due_j.
- If j starts at time $start_j$, it finishes at time $finish_j = start_j + time_j$.
- Lateness: $late_j = 0$ if finished before deadline, otherwise $late_j = finish_j - due_j$
- Goal: schedule all jobs to minimize maximum lateness = max $late_j$.

Aplication: Project management

Ex:

	1	2	3	4	5	6
$time_j$	3	2	1	4	3	2
due_j	6	8	9	9	14	15



[Try to find optimal solution for this example]

Minimizing Lateness: Greedy Algorithms

Greedy template. Process jobs in some order.

- [Shortest processing time first] Consider jobs in ascending order of processing time $time_j$.
- [Earliest deadline first] Consider jobs in ascending order of deadline due_j.
- [Smallest slack] Consider jobs in ascending order of slack $due_j - time_j$.

Minimizing Lateness: Greedy Algorithms

Greedy template. Process jobs in some order.

- [Shortest processing time first] Consider jobs in ascending order of processing time $time_j$.

	1	2
t_j	1	10
d_j	100	10

counterexample

- [Smallest slack] Consider jobs in ascending order of slack $due_j - time_j$.

	1	2
t_j	1	10
d_j	2	10

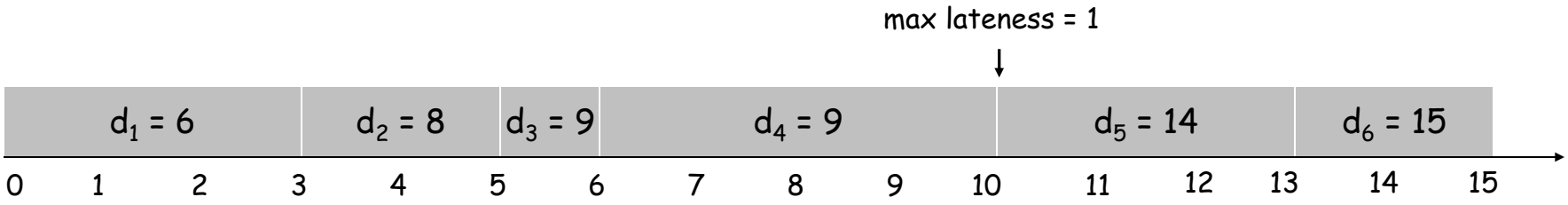
counterexample

Minimizing Lateness: Greedy Algorithm

Greedy algorithm. Earliest deadline first.

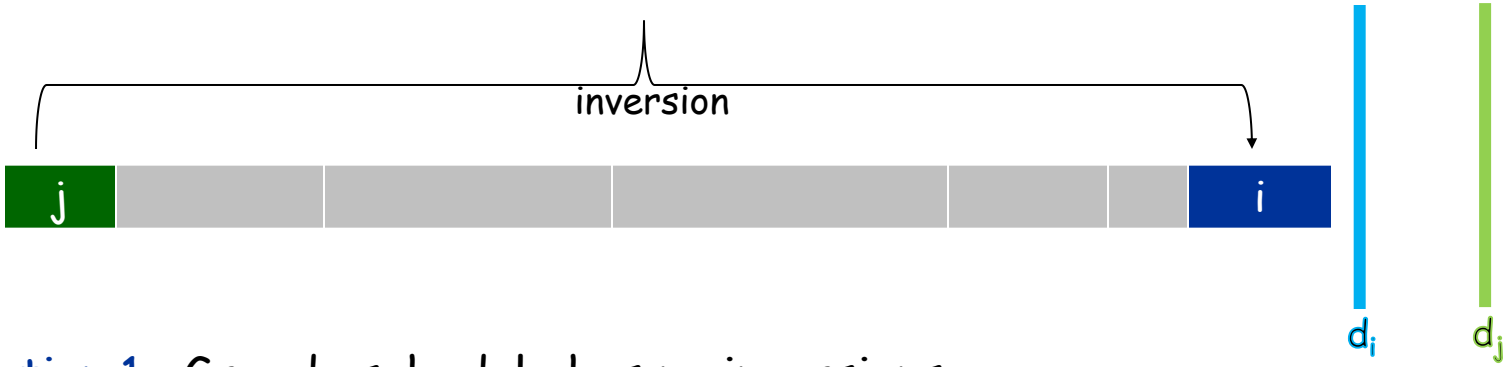
```
Sort n jobs by deadline so that d_1 ≤ d_2 ≤ … ≤ d_n

for j = 1 to n
   Assign job j to next available time period
```



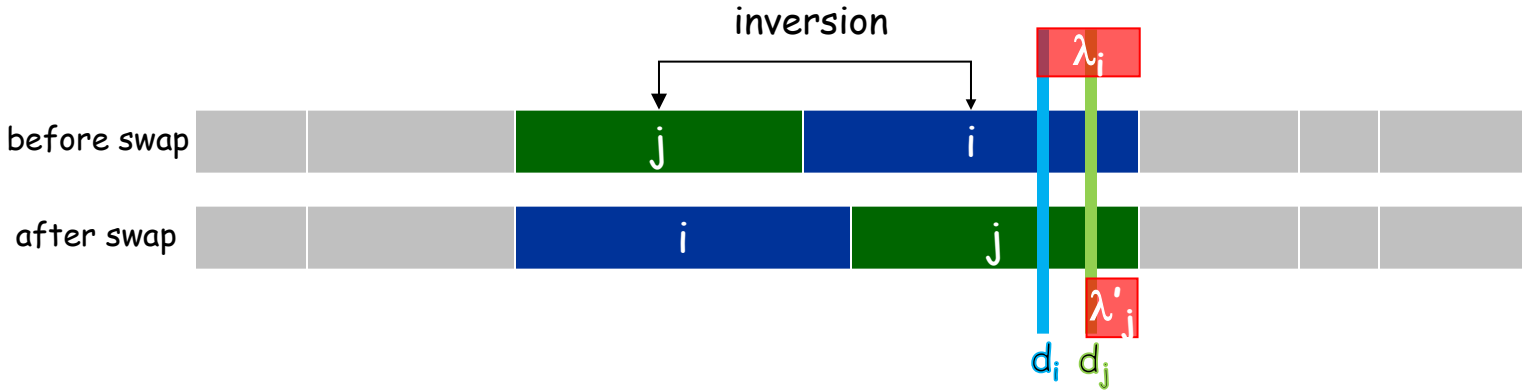
Minimizing Lateness: Idea of analysis

Def. An inversion in schedule S is a pair of jobs i and j such that: $d_i < d_j$ but j scheduled before i.



Observation 1. Greedy schedule has no inversions.

Observation 2. Swapping two adjacent, inverted jobs does not make solution worse (does not increase the max lateness)

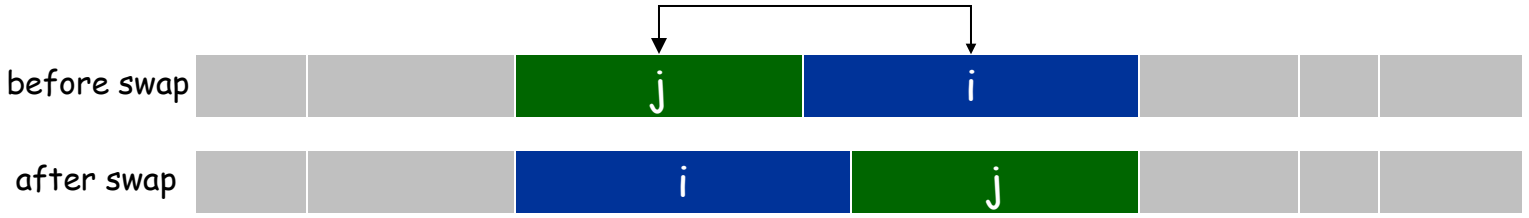


Minimizing Lateness: Idea of analysis

Swaps: Take OPT, keep swapping inverted jobs, brings it closer to greedy without making the solution worse

Repeating this we get a solution without any inversion (even non-adjacent, why?)

Reach solution where all items are in order of deadline => greedy solution (essentially; if assume dues dates are distinct, this is true)



Theorem. The Greedy algorithm in increasing order of due date is optimal

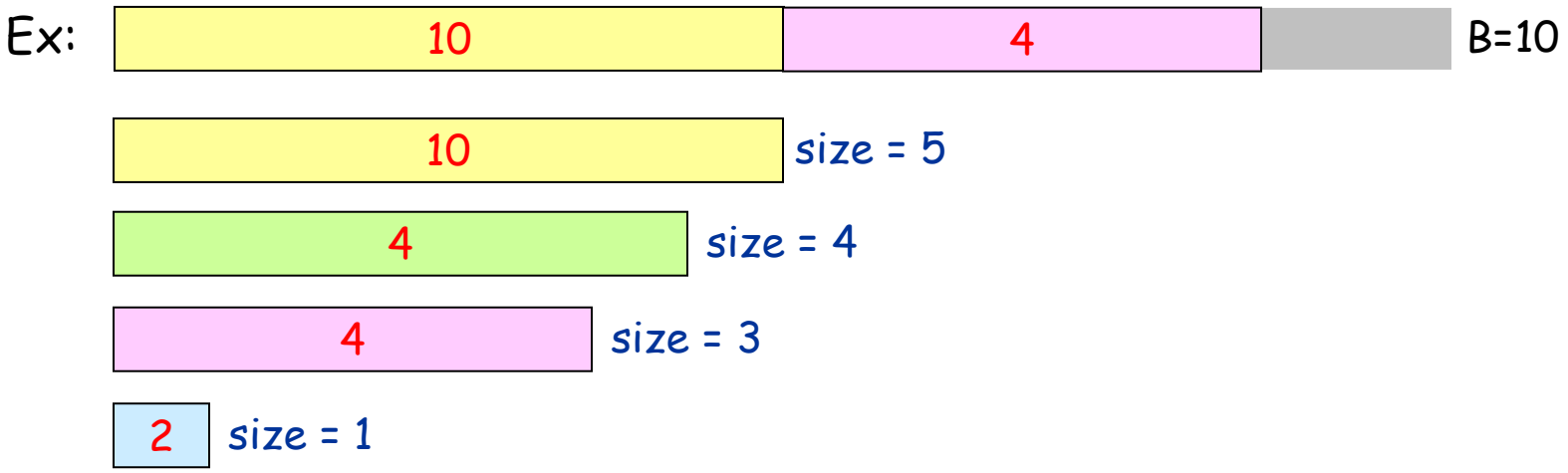
Fractional Knapsack Problem

Fractional Knapsack Problem

Knapsack Problem:

- You have a backpack of size B and several items
- Each item i has a size $size_i$ and value $value_i$
- Goal: Select items to put in the backpack that maximizes total value

Application: Project selection. (B is budget, size is cost, value is revenue)

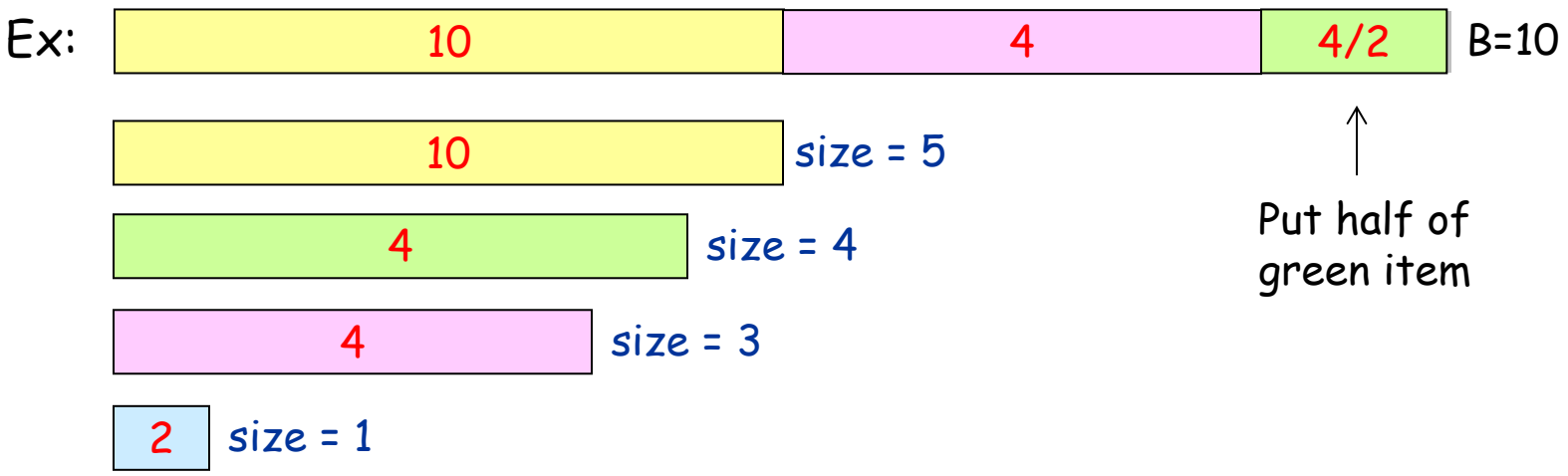


This is a harder problem, we will see in dynamic programming

Fractional Knapsack Problem

Fractional Knapsack Problem:

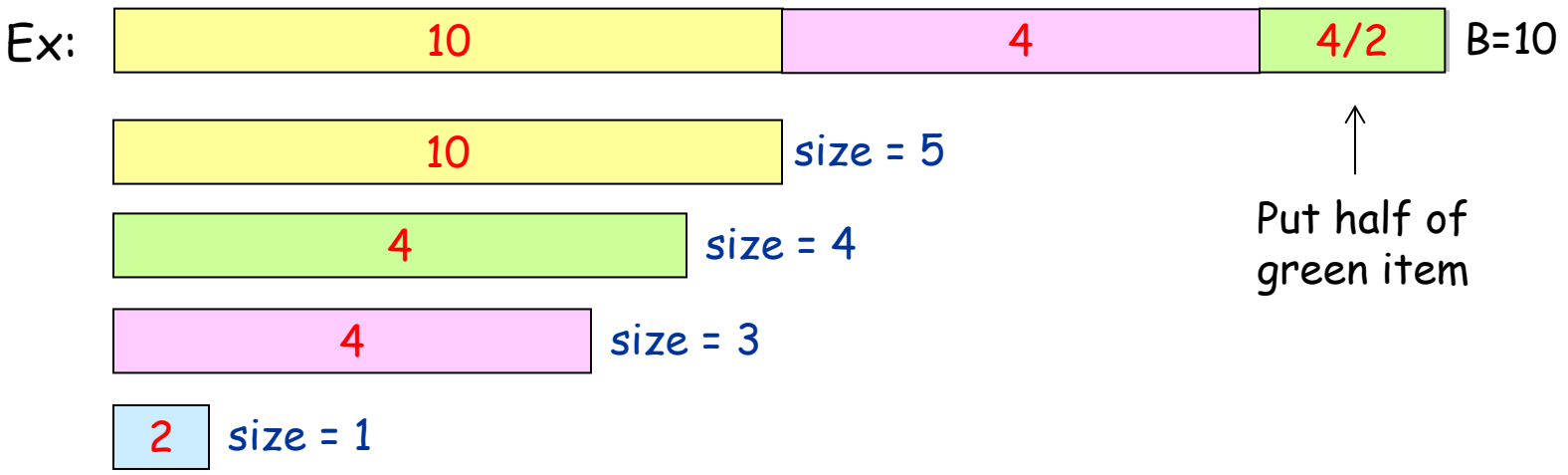
- You have a backpack of size B and several items
- Each item i has a size $size_i$ and value $value_i$
- Goal: Select items to put in the backpack that maximizes total value, can select just a fraction of an item (e.g. 10%)



Q: Can you see how to improve this solution?

A: Replace $\frac{1}{4}$ of green item by the blue item

Fractional Knapsack Problem



Q: Can you see how to improve this solution?

A: Replace "1 unit of size of green item" ($\frac{1}{4}$ of green item) by the blue item

Why it improves: Green item gives \$1 per size occupied

Blue item gives \$2 per size occupied

Fractional Knapsack Problem

Task: Give a greedy algorithm for the Fractional Knapsack Problem [Dantzig '57]

Greedy algorithm:

- sort items in decreasing order of value/size (value per unit of size occupied)
- Scan items in this order, add as much of the item as you can to the backpack

Why it woks?

- Swap argument outlined in previous slide

Theorem: Greedy by value/size is optimal.

Fractional Knapsack Problem

Does greedy with these item orders work? If it does, give a brief justification; if not, contruct a counterexample

1) Increasing size? (smallest items first)
No

2) Decreasing value? (highest value first)
No

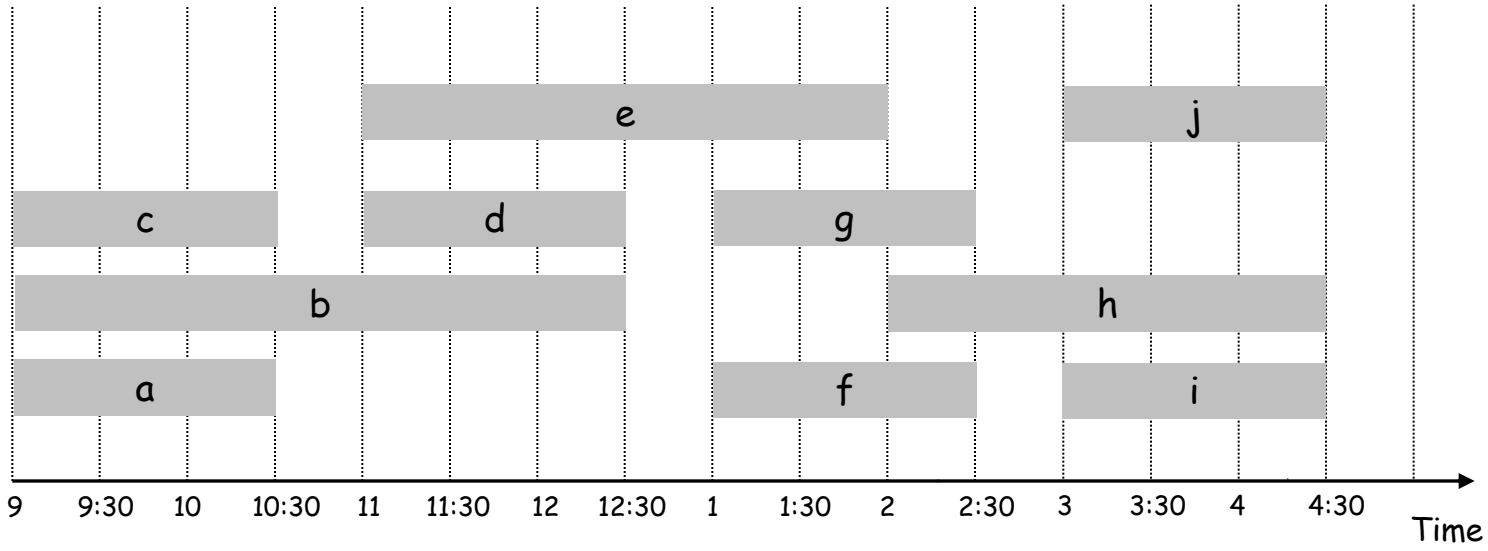
Interval Partitioning
(a non-swap based analysis)

Interval Partitioning

Interval partitioning.

- Lecture j starts at s_j and finishes at f_j.
- **Goal:** find minimum number of classrooms to schedule all lectures so that no two occur at the same time in the same room.
- (ignore overlap at start/finish)

Ex: This schedule uses 4 classrooms to schedule 10 lectures.

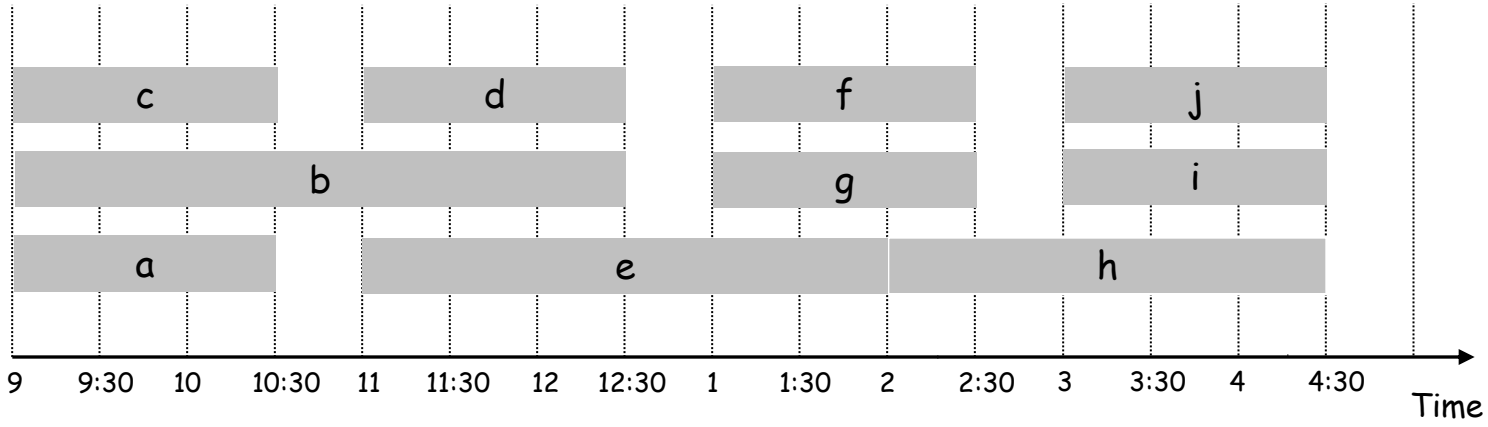


Interval Partitioning

Interval partitioning.

- Lecture j starts at s_j and finishes at f_j.
- **Goal:** find minimum number of classrooms to schedule all lectures so that no two occur at the same time in the same room.
- (ignore overlap at start/finish)

Ex: This schedule uses only 3.



Interval Partitioning: Lower Bound on Optimal Solution

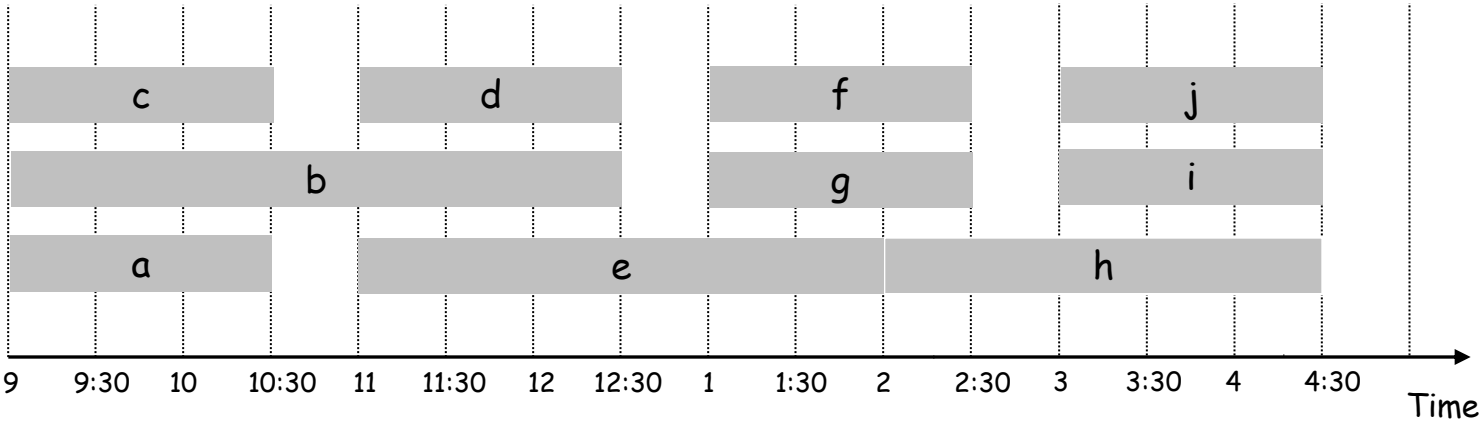
Def. The depth is defined as the maximum number of lectures that overlap at one given time

Key observation. Number of classrooms needed $\geq$ depth.

Ex: Depth of schedule below = 3 $\Rightarrow$ schedule below is optimal.

a, b, c all contain 9:30

Q. Does there always exist a schedule equal to depth of intervals?



Interval Partitioning: Greedy Algorithm

Greedy algorithm. Consider lectures in increasing order of start time: assign lecture to any compatible classroom.

```
Sort intervals by starting time so that s_1 ≤ s_2 ≤ ... ≤ s_n.
d ← 0   ← number of allocated classrooms

for j = 1 to n {
   if (lecture j is compatible with some classroom k)
      schedule lecture j in classroom k
   else
      allocate a new classroom d + 1
      schedule lecture j in classroom d + 1
      d ← d + 1
}
```

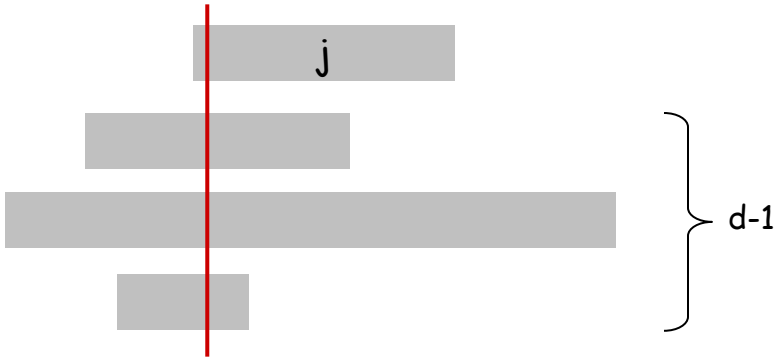
Interval Partitioning: Greedy Analysis

Observation. Greedy algorithm never schedules two incompatible lectures in the same classroom.

Theorem. Greedy algorithm is optimal.

Pf.

- Let d = number of classrooms that the greedy algorithm allocates.
- Classroom d is opened because we needed to schedule a job, say j, that is incompatible with all d-1 other classrooms.
- Since we sorted by start time, all these incompatibilities are caused by lectures that start no later than s_j.
- Thus, we have d lectures overlapping at time $s_j + \varepsilon$.
- Key observation $\Rightarrow$ all schedules use $\geq$ d classrooms. ▪



Interval Partitioning: Greedy Algorithm

Implementation. O(nd).

- For each classroom k, maintain the finish time of the last job added.
- Keep the classrooms in a list

[if (lecture j is compatible with some classroom k)]

Compare start time of j with the finish time of each class: O(d) time

[schedule lecture j in classroom k]

Replace the current finish time of class k to f_j: O(1) time

[allocate a new classroom] : O(1) time

[schedule lecture j in the new classroom]

Insert a new class in the list of classes with finish time f_j: O(1) time

Interval Partitioning: Greedy Algorithm

Implementation. O(n log d).

- For each classroom k, maintain the finish time of the last job added.
- Keep the classrooms in a heap

[if (lecture j is compatible with some classroom k)]

Compare start time of j with the finish time of the class at the root of the heap

[schedule lecture j in classroom k]

Change the priority of the root of heap to f_j

Update the heap : O(log d) time

[allocate a new classroom]

[schedule lecture j in the new classroom]

Insert a new class at the heap with priority f_j: O(log d)

Exercise: Optimal purchasing

Your friends are starting a security company that needs to obtain licenses for n different pieces of cryptographic software. Due to regulations, they can only obtain these licenses at the rate of at most one per month.

Each license is currently selling for a price of \$100. However, they are all becoming more expensive according to exponential growth curves: in particular, the cost of license j increases by a factor of $r_j > 1$ each month, where r_j is a given parameter. This means that if license j is purchased t months from now, it will cost $100 \cdot r_j^t$. We will assume that all the price growth rates are distinct; that is, $r_i \neq r_j$ for licenses $i \neq j$ (even though they start at the same price of \$100).

Obtain a strategy for buying all the n licenses while minimizing the total money spent

A: Buy in decreasing order of increse rate r_j (i.e. Buy first the one with largest r_j, then the second largest, etc.)

Why works? Any other order is worse: swap items out of order to improve

Other exercises

Chapter 4 of Kleinberg-Tardos' book

- Exercises 4, 5, 13, 14(a) [Dica: basta considerar os tempos de termino dos processos como possiveis pontos pra rodar status_check]