Today, we will learn how to use primal-dual LP setup to design online algorithms.

1 Online Primal-Dual Setup

The idea of online primal-dual algorithm is to simultaneously maintain a feasible primal solution \( x \) and a feasible dual solution \( y \). At \( t \)-th arrival, the algorithm updates both the primal and the dual while maintaining feasibility. Since weak-duality implies that a feasible dual gives a bound on the optimal primal value, we get the following lemma (which is a slight generalization because we allow a scaled dual to be feasible).

**Lemma 1.** For a minimization problem, if

(a) in every step \( t \) the primal increase is bounded by \( \beta \) times the dual increase, that is
\[
P(t) - P(t-1) \leq \beta (D(t) - D(t-1)),
\]
where \( P(t) = \text{primal objective} \) and \( D(t) = \text{dual objective at time } t \), and

(b) \( \frac{1}{\gamma} \) times the dual solution is dual-feasible,

then the algorithm is \( \beta \gamma \)-competitive.

2 Online Matching

As a warm-up to online primal-dual setup, we analyze the greedy algorithm for the online matching problem\(^1\). In online matching, edges of a graph are revealed one-by-one and the algorithm, which starts with \( M = \emptyset \), has to immediately and irrevocably decide whether to include the \( t \)-th edge \( e \) into matching \( M \). The algorithm wants to maximize the size of \( M \).

We will prove that the greedy algorithm, which selects the next edge \( e = (u, v) \) into \( M \) if both end points \( u, v \) are currently unmatched, gives a 2 competitive ratio (i.e., always maintains a matching size of at least half of the optimal offline matching size).

\(^1\)Pedantically, the analysis in this section for online matching should be called “online dual-fitting” instead of “online primal-dual” because the primal algorithm does not use dual variables to make its decisions, but the dual variables are only used for analysis. Since both ideas rely on weak-duality, we won’t distinguish.
Let's start by writing an LP relaxation for the max-matching problem, where we denote by $N^{(t)}(u)$ the edges incident to vertex $u$ till time $t$.

$$\begin{align*}
& \text{maximize } \sum_{e \in E^{(t)}} x_e^{(t)} \\
& \text{subject to } \sum_{e \in N^{(t)}(u)} x_e^{(t)} \leq 1 \quad \text{for all vertices } u \\
& \quad x_e^{(t)} \geq 0 \quad \text{for all } e
\end{align*}$$

Its dual program is given by:

$$\begin{align*}
& \text{minimize } \sum_u y_u^{(t)} \\
& \text{subject to } y_u^{(t)} + y_v^{(t)} \geq 1 \quad \text{for all edges } (u, v) \text{ till time } t \\
& \quad y_u^{(t)} \geq 0 \quad \text{for all vertices } u
\end{align*}$$

Consider the primal solution $x^{(0)}$ being all 0 in the beginning. We set $x_e^{(t)} = x_e^{(t-1)} + 1$ if $e$ is the $t$-th edge and gets selected by the greedy algorithm, and otherwise set $x_e^{(t)} = x_e^{(t-1)}$. For the dual, we start with $y^{(0)} = 0$. On arrival of $t$-th edge $e = (u, v)$, if both $u$ and $v$ are currently unmatched by the greedy algorithm then we set $y_u^{(t)} = y_v^{(t)} = 1$ and for every other vertex $u$ we set $y_u^{(t)} = y_u^{(t-1)}$. On the other hand, if on arrival of $t$-th edge $e = (u, v)$ either of vertex $u$ or $v$ is already matched, we set $y_u^{(t)} = y_v^{(t)} = y_u^{(t-1)}$ for all vertices. Next we show that such a setting of primal and dual variables satisfies the conditions in Lemma 1 (after making changes corresponding to maximization vs. minimization problem) with $\beta = 1/2$ and $\gamma = 1$.

First, note that the primal is always feasible because we only set $x_e = 1$ if the edge can be selected in the greedy matching. Next, to prove dual feasibility, we show the following invariant: all the vertices $u$ that have been matched by the greedy algorithm till time $t$ satisfy that $y_u^{(t)} = 1$. This invariant is clearly true at $t = 0$. Since we only increase $y_u^{(t)}$ (compared to $y_u^{(t-1)}$), we only need to check the invariant for the new $t$-th edge $e = (u, v)$. Here the invariant holds because if both $u, v$ are currently unmatched then we select it into matching and set $y_u^{(t)} = y_v^{(t)} = 1$. Given the invariant, dual feasibility immediately follows because for any edge $(u, v)$ that does not satisfy $y_u^{(t)} + y_v^{(t)} \geq 1$, we should have included it into the greedy matching.

Finally, note that on each edge's arrival, the increase in primal objective $\sum_{e \in E^{(t)}} x_e^{(t)} - \sum_{e \in E^{(t-1)}} x_e^{(t-1)}$ is at least half of the increase in dual objective $\sum_u y_u^{(t)} - \sum_u y_u^{(t-1)}$. This is because the dual only increases on arrival of $t$-th edge $(u, v)$ when both $u$ and $v$ are currently unmatched in the greedy solution, and then dual increases by 2 and the primal increases by 1. Thus we have shown a competitive ratio of 2 by Lemma 1.
3 Online Fractional Set Cover

Next we will apply the online-primal dual framework to an online variant of the set cover problem. Let’s first recall the offline weighted set cover problem from Lecture 7: You are given a universe of \( m \) elements \( U = \{1, \ldots, n\} \) and a family of \( m \) subsets of \( U \) called \( S \subseteq 2^U \). For each \( S \in S \), there is a cost \( c_S \). Your task is to find a cover \( C \subseteq S \) of minimum cost \( \sum_{S \in C} c_S \). A set \( C \) is a cover if for each \( e \in U \) there is an \( S \in C \) such that \( e \in S \). Alternatively, you could say \( \bigcup_{S \in C} S = U \). We assume that each element of \( U \) is included in at least one \( S \in S \). So in other words \( S \) is a feasible cover. Otherwise, there might not be a feasible solution.

Today, we will consider an online variant of a relaxation of this problem where we are allowed to fractionally select sets and the elements to be covered are revealed one-by-one. So, our goal is to solve the following kind of linear program online.

\[
\begin{align*}
\text{minimize} & \quad \sum_{S \in S} c_S x_S \\
\text{subject to} & \quad \sum_{S: e \in S} x_S \geq 1 \quad \text{for all } e \in U \\
& \quad x_S \geq 0 \quad \text{for all } S \in S
\end{align*}
\]

We have to maintain a feasible solution \( x^{(t)} \) to the linear inequalities. In the \( t \)-th step, the \( t \)-th element arrives and therefore we get to know the \( t \)-th coverage constraint. Possibly, the solution \( x^{(t-1)} \) we had so far is infeasible now. In this case, we may only increase variables to get to the solution \( x^{(t)} \), which is feasible again.

Recall the dual of the set cover LP

\[
\begin{align*}
\text{maximize} & \quad \sum_{e \in U} y_e \\
\text{subject to} & \quad \sum_{e \in S} y_e \leq c_S \quad \text{for all } S \in S \\
& \quad y_e \geq 0 \quad \text{for all } e \in U
\end{align*}
\]

We will use a primal-dual algorithm. That is, besides maintaining a primal solution \( x^{(t)} \), we will also maintain a dual solution \( y^{(t)} = (y_1, y_2, \ldots, y_t) \). In step \( t \), variable \( y_t \) is added to the dual LP and we can only set its value (i.e., we do not change \( y_1, \ldots, y_{t-1} \)). We want to eventually use Lemma 1.

3.1 Approach for Fractional Online Set Cover

When choosing \( x^{(t)} \) and \( y_t \), our primary goal is that they have similar objective-function values so that Property (a) in Lemma 1 holds with a small \( \beta \).

So, let us figure out what we would like to do. Suppose we are in step \( t \). That is, element \( t \) arrives and we observe a new constraint \( \sum_{S: t \in S} x_S \geq 1 \) in the primal LP. In the dual,
a new variable $y_t$ arrives. Our current solution is $x^{(t-1)}$. It fulfills all constraints except maybe the new one. If we also have $\sum_{S: t \in S} x_S^{(t-1)} \geq 1$, then there is nothing to do because we can keep the old solution as the new one by setting $x^{(t)} = x^{(t-1)}$, $y_t = 0$.

In the case $\sum_{S: t \in S} x_S^{(t-1)} < 1$, we will have to increase some primal variables to get a feasible $x^{(t)}$. Of course, $x^{(t)}$ will be more expensive than $x^{(t-1)}$. We reflect this additional cost in the value of $y_t$, all other dual variables remain unchanged.

Let us slowly increase $x$ starting from $x^{(t-1)}$ and simultaneously increase $y_t$ starting from 0. We do this in infinitesimal steps over continuous time.

We are at any point in time for which still $\sum_{S: t \in S} x_S < 1$. We increase $x_S$ by $dx_S$. To account for the increased cost, we increase $y_t$ by $dy$ at the same time. The dual objective function increases by $dy$ this way. This is at least $(\sum_{S: t \in S} x_S)dy$ because $\sum_{S: t \in S} x_S < 1$. Simultaneously, the primal objective function increases by $\sum_{S: t \in S} c_S dx_S$. If we set $dx_S = \frac{x_S}{c_S} dy$ for all $S$ for which $t \in S$, then these changes exactly match up.

Ideally, we would follow exactly this pattern. However, notice that we start from $x^{(0)} = 0$, so all increases would be 0. Therefore, let $\eta > 0$ be a very small constant and set

$$dx_S = \frac{1}{c_S} (x_S + \eta) dy .$$

(1)

This is a differential equation. We try a solution of the form $x_S = C_1 e^{C_2 y} + C_3$. Then we have $\frac{dx_S}{dy} = C_2 (x_S - C_3)$. So comparing with (1), we get $C_3 = -\eta$ and $C_2 = \frac{1}{c_S}$. Moreover, because for $y = 0$ we have $x_S = x_S^{(t-1)}$, we get $C_1 = x_S^{(t-1)} + \eta$, This way

$$x_S^{(t)} + \eta = e^{\frac{1}{c_S} y_t} \left( x_S^{(t-1)} + \eta \right) ,$$

where $y_t$ is the smallest value s.t. $x^{(t)}$ is feasible to the first $t$ constraints of the primal LP.

### 3.2 Algorithm

Let us now use the above approach to design an algorithm for fractional online set cover. For our algorithm, set $\eta = \frac{1}{m}$ and initialize all $x_S = 0$. In the $t$-th step, when element $t$ arrives, introduce the primal constraint $\sum_{S: t \in S} x_S \geq 1$ and a dual variable $y_t$. We initialize $y_t = 0$ and update it as follows: For each $S$ with $t \in S$, increase $x_S$ from $x_S^{(t-1)}$ to $x_S^{(t)}$ by

$$x_S^{(t)} + \eta = e^{\frac{1}{c_S} y_t} \left( x_S^{(t-1)} + \eta \right) ,$$

where $y_t$ is the smallest value such that $x^{(t)}$ becomes a feasible solution.

**Theorem 2.** The algorithm is $O(\log m)$-competitive for online fractional set cover.

**Proof.** We will verify the conditions of Lemma 1 with $\beta = 2$ and $\gamma = \ln(m + 1)$. 

We start by property (a). Consider the \( t \)-th step; element \( t \) arrives in this step. We have to relate \( P(t) - P(t-1) = \sum_S c_S (x_S^{(t)} - x_S^{(t-1)}) \) to \( y_t \). For every set \( S \) such that \( t \in S \), we have
\[
x_S^{(t)} + \eta = e^{\frac{1}{c_S} y_t} \left( x_S^{(t-1)} + \eta \right),
\]
and therefore
\[
x_S^{(t-1)} + \eta = e^{-\frac{1}{c_S} y_t} \left( x_S^{(t)} + \eta \right).
\]
This lets us write the increase of \( x_S \) as follows
\[
x_S^{(t)} - x_S^{(t-1)} = (x_S^{(t)} + \eta) - e^{-\frac{1}{c_S} y_t} \left( x_S^{(t)} + \eta \right) = \left( 1 - e^{-\frac{1}{c_S} y_t} \right) \left( x_S^{(t)} + \eta \right) \leq \frac{1}{c_S} \left( x_S^{(t)} + \eta \right) y_t.
\]
This way, we can bound the primal increase by
\[
P(t) - P(t-1) \leq \sum_{S: t \in S} c_S \frac{1}{c_S} \left( x_S^{(t)} + \eta \right) y_t = \sum_{S: t \in S} x_S^{(t)} y_t + \sum_{S: t \in S} \eta y_t \leq 2 y_t,
\]
because \( \sum_{S: t \in S} x_S^{(t)} = 1 \) (otherwise we would have increased variables by too much) and \( \sum_{S: t \in S} \eta \leq m \eta = 1 \).

Now, we turn to property (b). Consider a fixed \( S \in \mathcal{S} \). We will verify that the dual constraint for set \( S \) is fulfilled. By our algorithm if \( t \in S \) then
\[
y_t = c_S \ln(x_S^{(t)} + \eta) - c_S \ln(x_S^{(t-1)} + \eta),
\]
onotherwise \( x_S^{(t)} = x_S^{(t-1)} \) and so \( c_S \ln(x_S^{(t)} + \eta) - c_S \ln(x_S^{(t-1)} + \eta) = 0 \).
This lets us write the sum \( \sum_{t \in S} y_t \) as
\[
\sum_{t \in S} y_t = \sum_{t=1}^{n} \left( c_S \ln(x_S^{(t)} + \eta) - c_S \ln(x_S^{(t-1)} + \eta) \right) = c_S \ln \left( \frac{x_S^{(n)} + \eta}{x_S^{(0)} + \eta} \right).
\]
Furthermore, \( x_S^{(0)} \geq 0 \) because variables are never negative and \( x_S^{(n)} \leq 1 \) because it does not make sense to increase variables beyond 1. So
\[
\sum_{t \in S} y_t \leq c_S \ln \left( \frac{1 + \eta}{\eta} \right) = c_S \ln(m + 1) = \gamma c_S.
\]

It is possible to extend Theorem 2 to an \( O(\log n \cdot \log m) \) competitive algorithm for the online set cover problem where the algorithm has to select sets integrally. The idea is to do randomized rounding, try this as an exercise or see [1].

Notes

The lecture is partly based on Thomas Kesselheim’s notes\(^2\).

References