Integer Programming
ISE 418

Lecture 10

Dr. Ted Ralphs

Reading for This Lecture

- Nemhauser and Wolsey II.3.6

The Efficiency of Branch and Bound

- In general, our goal is to solve the problem at hand as quickly as possible.
- The overall solution time is the product of the number of nodes enumerated and the time to process each node.
- Typically, by spending more time in processing, we can achieve a reduction in tree size by computing stronger (closer to optimal) bounds.
- This highlights another of the many tradeoffs we must navigate.
- Our goal in bounding is to achieve a balance between the strength of the bound and the efficiency with which we can compute it.
- How do we compute bounds?
  - Relaxation: Relax some of the constraints and solve the resulting mathematical optimization problem.
  - Duality: Formulate a "dual" problem and find a feasible to it.
- In practice, we will use a combination of these two closely-related approaches.

Relaxation

As usual, we consider the MILP

$$z_{IP} = \max\{c^\top x \mid x \in \mathcal{S}\}, \qquad \text{(MILP)}$$

where

$$\mathcal{P} = \{x \in \mathbb{R}^n \mid Ax \leq b\} \qquad \text{(FEAS-LP)}$$

$$\mathcal{S} = \mathcal{P} \cap (\mathbb{Z}^p_+ \times \mathbb{R}^{n-p}_+) \qquad \text{(FEAS-MIP)}$$

Definition 1. *A* relaxation *of* (MILP) *is a maximization problem defined as*

$$z_R = \max\{z_R(x) \mid x \in \mathcal{S}_R\}$$

with the following two properties:

$$\begin{aligned} \mathcal{S} &\subseteq \mathcal{S}_R \\ c^\top x &\leq z_R(x), \ \forall x \in \mathcal{S}. \end{aligned}$$

Importance of Relaxations

- The main purpose of a relaxation is to obtain an upper bound on z_{IP}.
- Solving a relaxation is one simple method of bounding in branch and bound.
- The idea is to choose a relaxation that is much easier to solve than the original problem, but still yields a bound that is "strong enough."
- Note that the relaxation must be solved to optimality to yield a valid bound.
- We consider three types of "formulation-based" relaxations.
  - LP relaxation
  - Combinatorial relaxation
  - Lagrangian relaxation
- Relaxations are also used in some other bounding schemes we'll look at.

Dual Functions from Relaxations

- Note that relaxations can be used to obtain dual functions!
- The value function of any relaxation is a solution to the general dual we discussed in Lecture 8.
- In particular, recall that we have already seen that the value function of the LP relaxation is the convex envelope of the exact value function.

Aside: How Do You Spell "Lagrangian?"

- Some spell it "Lagrangean."
- Some spell it "Lagrangian."
- We ask Google.
- In 2002:
  - "Lagrangean" returned 5,620 hits.
  - "Lagrangian" returned 14,300 hits.
- In 2007:
  - "Lagrangean" returns 208,000 hits.
  - "Lagrangian" returns 5,820,000 hits.
- In 2010:
  - "Lagrangean" returns 110,000 hits (and asks "Did you mean: Lagrangian?")
  - "Lagrangian" returns 2,610,000 hits.
- In 2014 (strange regression!):
  - "Lagrangean" returns 1,140,000 hits
  - "Lagrangian" returns 1,820,000 hits.
- In 2019 (huh?):
  - "Lagrangean" returns 197,000 hits
  - "Lagrangian" returns 6,680,000 hits.

Obtaining and Using Relaxations

- Properties of relaxations
  - If a relaxation of (MILP) is infeasible, then so is (MILP).
  - If $z_R(x) = c^\top x$, then for $x^* \in \operatorname{argmax}_{x \in S_R} z_R(x)$, if $x^* \in \mathcal{S}$, then x^* is optimal for (MILP).
- The easiest way to obtain relaxations of (MILP) is to relax some of the constraints defining the feasible set $\mathcal{S}$.
- It is "obvious" how to obtain an LP relaxation, but combinatorial relaxations are not as obvious.

Example: Traveling Salesman Problem

The TSP is a combinatorial problem $(E, \mathcal{F})$ whose ground set is the edge set of a graph $G = (V, E)$.

- $V = \{1, \ldots, n\}$ is the set of customers.
- E is the set of travel links between the customers.

A feasible solution is a subset of E consisting of edges of the form $\{i, \sigma(i)\}$ for $i \in V$, where σ is a simple permutation V specifying the order in which the customers are visited.

IP Formulation:

$$\begin{array}{rcll} \sum_{j=1}^{n} x_{ij} & = & 2 & \forall i \in V \setminus \{1\} \\ \sum_{\substack{i \in S \\ j \notin S}} x_{ij} & \geq & 2 & \forall S \subset V,\ |S| > 1. \end{array}$$

where x_{ij} is a binary variable indicating whether $\sigma(i) = j$.

Combinatorial Relaxations of the TSP

- The Traveling Salesman Problem has several well-known combinatorial relaxations.

- Assignment Problem
  - The problem of assigning n people to n different tasks.
  - Can be solved in polynomial time.
  - Obtained by dropping the subtour elimination constraints and the upper bounds on the variables.

- Minimum 1-tree Problem
  - A *1-tree* in a graph is a spanning tree of nodes $\{2, \ldots n\}$ plus exactly two edges incident to node one.
  - A minimum 1-tree can be found in polynomial time.
  - This relaxation is obtained by dropping all subtour elimination constraints involving node 1 and also all degree constraints not involving node 1.

Exploiting Relaxations

- How can we use our ability to solve a relaxation to full advantage?
- The most obvious way is simply to straightforwardly use the relaxation to obtain a bound.
- However, by solving the relaxation repeatedly, we can get additional information.
- For example, we can generate extreme points of $\mathrm{conv}(\mathcal{S}_R)$.
- In an indirect way (using the Farkas Lemma), we can even obtain facet-defining inequalities for $\mathrm{conv}(\mathcal{S}_R)$.
- We can use this information to strengthen the original formulation.
- This is one of the basic principles of many solution methods.

Lagrangian Relaxation

- A Lagrangian relaxation is obtained by relaxing a set of constraints from the original formulation to improve tractability.
- However, we also try to improve the bound by modifying the objective function, penalizing violation of the dropped constraints.
- Consider a pure IP defined by

$$\begin{aligned} \max\ & c^\top x \\ \text{s.t. } & A'x \leq b' \\ & A''x \leq b'' \\ & x \in \mathbb{Z}^n_+, \end{aligned} \tag{IP}$$

  where $\mathcal{S}_R = \{x \in \mathbb{Z}^n_+ \mid A'x \leq b'\}$ bounded and optimization over S_R is "easy."

- Lagrangian Relaxation:

$$LR(u) : z_{LR}(u) = ub'' + \max_{x \in \mathcal{S}_R} \{(c - uA'')x\}.$$

Properties of the Lagrangian Relaxation

- For any $u \geq 0$, $LR(u)$ is a relaxation of (IP) (why?).
- Solving $LR(u)$ yields an upper bound on the value of an optimal solution.
- Recalling LP duality, one can think of u as a vector of "dual variables."
- The *Lagrangian dual* problem is that of determining

$$\min_{u \geq 0} LR(u),$$

  the "best bound" that can be obtained by optimization over $\mathcal{S}_R$.
- This bound is at least as good as the bound yielded by solving the LP relaxation.
- We will examine this problem in much more detail later in the course.

The Lagrangian Dual Function

- We can obtain a dual function from a Lagrangian relaxation by letting

$$L(\beta, u) = \max_{x \in \mathcal{S}_R(\beta')} (c - uA'')x + u\beta'',$$

where $\mathcal{S}_R(d) = \{x \in \mathbb{Z}^n_+ \mid A'x \leq d\}$

- For fixed β, the function $L(\cdot, u)$ is the max of affine functions, i.e., convex piecewise polyhedral.
- Then the Lagrangian dual function, ϕ_{LD}, is

$$\phi_{LD}(\beta) = \min_{u \geq 0} L(\beta, u)$$

- This is the minimum of convex piecewise polyhedral functions and bounds the value function from above (we are in the maximization case here).
- We will see a number of ways of efficiently computing $\phi_{LD}(b)$ later in the course.

Relaxations from Conceptual Reformulations

- From what we have seen so far, we have two conceptual reformulations of a given integer optimization problem.
- The first is in terms of *disjunction*:

$$\max \left\{ c^\top x \mid x \in \left(\bigcup_{i=1}^{k} \mathcal{P}_i + \mathrm{intcone}\{r^1, \dots, r^t\} \right) \right\} \qquad \text{(DIS)}$$

- The second is in terms of *valid inequalities*:

$$\max \left\{ c^\top x \mid x \in \mathrm{conv}(\mathcal{S}) \right\} \qquad \text{(CP)}$$

  where $\mathcal{S}$ is the feasible region.
- In principle, if we had a method for generating either of these reformulations, this would lead to a practical method of solution.
- Instead, we usually begin with a relaxation derived from one of these two reformulations and iteratively approximate the full formulation.

A Generic Algorithmic Framework

- Many algorithms in optimization consist of the iterative solution of a certain relaxation or "dual".
- The relaxation or dual is improved dynamically until an optimality criterion is achieved.
- A simple algorithm for solving MILPs is to start by solving the LP relaxation to obtain

$$\hat{x} \in \mathrm{argmax}_{x \in \mathcal{P}} c^\top x$$

and the upper bound $U = c^\top \hat{x} \geq z_{\mathsf{IP}}$

- Then determine either a valid disjunction or a valid inequality that is *violated* by $\hat{x}$ and "add" it to the relaxation.
- Re-solve the strengthened relaxation and continue this process until $U = z_{\mathsf{IP}}$ (the solution to the relaxation is in $\mathcal{S}$).
- This vague algorithm is, at a high level, how we solve MILPs and we will see that branch-and-bound fits into this framework.
- The condition that $U = z_{\mathsf{IP}}$ is the basic optimality condition used in a wide range of optimization algorithms.

The Branch and Bound Tree as a "Meta-Relaxation"

- The branch-and-bound tree itself encodes a relaxation of our original problem, as we mentioned in the last lecture.
- As observed previously, the set T of leaf nodes of the tree (including those that have been pruned) constitute a valid disjunction, as follows.
  - When we branch using admissible disjunctions, we associate with each $t \in T$ a polyhedron X_t described by the imposed branching constraints.
  - The collection $\{X_t\}_{t \in T}$ then defines a disjunction.
- The *subproblem* associated with node i is an integer program with feasible region $\mathcal{S} \cap \mathcal{P} \cap X_t$.
- The problem

$$\max_{t \in T} \max_{x \in \mathcal{P} \cap X_t} c^\top x \tag{OPT}$$

  is then a relaxation according to our definition.
- Branch and bound can be seen as a method of iteratively strengthening this relaxation.
- We will later see how we can add valid inequalities to the constraint of $\mathcal{P} \cap X_t$ to strengthen further.