Disciplined Convex Programming and CVX

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Outline

- cone program solvers
- modeling systems
- disciplined convex programming
- CVX (CVXPY, Convex.jl)

Cone program solvers

- **LP solvers**
  - many, open source and commercial
- **cone solvers**
  - each handles combinations of a subset of LP, SOCP, SDP, EXP cones
  - open source: SDPT3, SeDuMi, CVXOPT, CSDP, ECOS, SCS, . . .
  - commercial: Mosek, Gurobi, Cplex, . . .
- you'll write a basic cone solver later in the course

Transforming problems to cone form

- lots of tricks for transforming a problem into an equivalent cone program
  - introducing slack variables
  - introducing new variables that upper bound expressions
- these tricks greatly extend the applicability of cone solvers
- writing code to carry out this transformation is painful
- **modeling systems** automate this step

Modeling systems

a typical modeling system

- automates transformation to cone form; supports
  - declaring optimization variables
  - describing the objective function
  - describing the constraints
  - choosing (and configuring) the solver
- when given a problem instance, calls the solver
- interprets and returns the solver's status (optimal, infeasible, . . .)
- (when solved) transforms the solution back to original form

Some current modeling systems

- AMPL & GAMS (proprietary)
  - developed in the 1980s, still widely used in traditional OR
  - no support for convex optimization
- YALMIP ('Yet Another LMI Parser', matlab)
  - first object-oriented convex optimization modeling system
- CVX (matlab)
- CVXPY (python, GPL)
- Convex.jl (Julia, GPL, merging into JUMP)
- CVX, CVXPY, and Convex.jl collectively referred to as CVX*

Disciplined convex programming

- describe objective and constraints using expressions formed from
  - a set of basic atoms (affine, convex, concave functions)
  - a restricted set of operations or rules (that preserve convexity)
- modeling system keeps track of affine, convex, concave expressions
- rules ensure that
  - expressions recognized as convex are convex
  - but, some convex expressions are not recognized as convex
- problems described using DCP are convex by construction
- all convex optimization modeling systems use DCP

CVX

- uses DCP
- runs in Matlab, between the `cvx_begin` and `cvx_end` commands
- relies on SDPT3 or SeDuMi (LP/SOCP/SDP) solvers
- refer to user guide, online help for more info
- the CVX example library has more than a hundred examples

Example: Constrained norm minimization

```
A = randn(5, 3);
b = randn(5, 1);
cvx_begin
    variable x(3);
    minimize(norm(A*x - b, 1))
    subject to
        -0.5 <= x;
         x <= 0.3;
cvx_end
```

- between `cvx_begin` and `cvx_end`, `x` is a CVX variable
- statement `subject to` does nothing, but can be added for readability
- inequalities are intepreted elementwise

What CVX does

after `cvx_end`, CVX

- transforms problem into an LP
- calls solver `SDPT3`
- overwrites (object) `x` with (numeric) optimal value
- assigns problem optimal value to `cvx_optval`
- assigns problem status (which here is `Solved`) to `cvx_status`

(had problem been infeasible, `cvx_status` would be `Infeasible` and `x` would be `NaN`)

Variables and affine expressions

- declare variables with `variable name[(dims)] [attributes]`
  - `variable x(3);`
  - `variable C(4,3);`
  - `variable S(3,3) symmetric;`
  - `variable D(3,3) diagonal;`
  - `variables y z;`
- form affine expressions
  - `A = randn(4, 3);`
  - `variables x(3) y(4);`
  - `3*x + 4`
  - `A*x - y`
  - `x(2:3)`
  - `sum(x)`

Some functions

function	meaning	attributes
`norm(x, p)`	$\|x\|_p$	cvx
`square(x)`	x^2	cvx
`square_pos(x)`	$(x_+)^2$	cvx, nondecr
`pos(x)`	x_+	cvx, nondecr
`sum_largest(x,k)`	$x_{[1]} + \cdots + x_{[k]}$	cvx, nondecr
`sqrt(x)`	$\sqrt{x} \quad (x \geq 0)$	ccv, nondecr
`inv_pos(x)`	$1/x \quad (x > 0)$	cvx, nonincr
`max(x)`	$\max\{x_1, \ldots, x_n\}$	cvx, nondecr
`quad_over_lin(x,y)`	$x^2/y \quad (y > 0)$	cvx, nonincr in y
`lambda_max(X)`	$\lambda_{\max}(X) \quad (X = X^T)$	cvx
`huber(x)`	$\begin{cases} x^2, & \|x\| \leq 1 \\ 2\|x\| - 1, & \|x\| > 1 \end{cases}$	cvx

Composition rules

- can combine atoms using valid composition rules, *e.g.*:
  - a convex function of an affine function is convex
  - the negative of a convex function is concave
  - a convex, nondecreasing function of a convex function is convex
  - a concave, nondecreasing function of a concave function is concave

Composition rules — multiple arguments

- for convex h, $h(g_1, \ldots, g_k)$ is recognized as convex if, for each i,
  - g_i is affine, or
  - g_i is convex and h is nondecreasing in its ith arg, or
  - g_i is concave and h is nonincreasing in its ith arg

- for concave h, $h(g_1, \ldots, g_k)$ is recognized as concave if, for each i,
  - g_i is affine, or
  - g_i is convex and h is nonincreasing in ith arg, or
  - g_i is concave and h is nondecreasing in ith arg

Valid (recognized) examples

`u`, `v`, `x`, `y` are scalar variables; `X` is a symmetric 3×3 variable

- convex:
  - `norm(A*x - y) + 0.1*norm(x, 1)`
  - `quad_over_lin(u - v, 1 - square(v))`
  - `lambda_max(2*X - 4*eye(3))`
  - `norm(2*X - 3, 'fro')`

- concave:
  - `min(1 + 2*u, 1 - max(2, v))`
  - `sqrt(v) - 4.55*inv_pos(u - v)`

Rejected examples

`u`, `v`, `x`, `y` are scalar variables

- neither convex nor concave:
  - `square(x) - square(y)`
  - `norm(A*x - y) - 0.1*norm(x, 1)`

- rejected due to limited DCP ruleset:
  - `sqrt(sum(square(x)))` (is convex; could use `norm(x)`)
  - `square(1 + x^2)` (is convex; could use `square_pos(1 + x^2)`, or `1 + 2*pow_pos(x, 2) + pow_pos(x, 4)`)

Sets

- some constraints are more naturally expressed with convex sets
- sets in CVX work by creating unnamed variables constrained to the set
- examples:
  - `semidefinite(n)`
  - `nonnegative(n)`
  - `simplex(n)`
  - `lorentz(n)`
- `semidefinite(n)`, say, returns an unnamed (symmetric matrix) variable that is constrained to be positive semidefinite

Using the semidefinite cone

variables: `X` (symmetric matrix), `z` (vector), `t` (scalar)
constants: `A` and `B` (matrices)

- `X == semidefinite(n)`
  - means $X \in \mathbf{S}_+^n$ (or $X \succeq 0$)
- `A*X*A' - X == B*semidefinite(n)*B'`
  - means $\exists\, Z \succeq 0$ so that $AXA^T - X = BZB^T$
- `[X z; z' t] == semidefinite(n+1)`
  - means $\begin{bmatrix} X & z \\ z^T & t \end{bmatrix} \succeq 0$

Objectives and constraints

- **objective** can be
  - `minimize(convex expression)`
  - `maximize(concave expression)`
  - omitted (feasibility problem)
- **constraints** can be
  - `convex expression <= concave expression`
  - `concave expression >= convex expression`
  - `affine expression == affine expression`
  - omitted (unconstrained problem)

More involved example

```
A = randn(5);
A = A'*A;
cvx_begin
    variable X(5, 5) symmetric;
    variable y;
    minimize(norm(X) - 10*sqrt(y))
    subject to
        X - A == semidefinite(5);
        X(2,5) == 2*y;
        X(3,1) >= 0.8;
        y <= 4;
cvx_end
```

Defining new functions

- can make a new function using existing atoms
- **example:** the convex deadzone function

$$f(x) = \max\{|x| - 1, 0\} = \begin{cases} 0, & |x| \leq 1 \\ x - 1, & x > 1 \\ 1 - x, & x < -1 \end{cases}$$

- create a file `deadzone.m` with the code

```
function y = deadzone(x)
y = max(abs(x) - 1, 0)
```

- `deadzone` makes sense both within and outside of CVX

Defining functions via incompletely specified problems

- suppose $f_0, \ldots, f_m$ are convex in (x, z)
- let $\phi(x)$ be optimal value of convex problem, with variable z and parameter x

$$
\begin{array}{ll}
\mbox{minimize} & f_0(x,z) \\
\mbox{subject to} & f_i(x,z) \leq 0, \quad i=1,\ldots,m \\
& A_1 x + A_2 z = b
\end{array}
$$

- ϕ is a convex function
- problem above sometimes called *incompletely specified* since x isn't (yet) given
- an incompletely specified concave maximization problem defines a concave function

CVX functions via incompletely specified problems

implement in cvx with

```
function cvx_optval = phi(x)
cvx_begin
    variable z;
    minimize(f0(x, z))
    subject to
        f1(x, z) <= 0; ...
        A1*x + A2*z == b;
cvx_end
```

- function `phi` will work for numeric `x` (by solving the problem)
- function `phi` can also be used inside a `CVX` specification, wherever a convex function can be used

Simple example: Two element max

- create file `max2.m` containing

```
function cvx_optval = max2(x, y)
cvx_begin
    variable t;
    minimize(t)
    subject to
        x <= t;
        y <= t;
cvx_end
```

- the constraints define the epigraph of the max function
- could add logic to return `max(x,y)` when `x`, `y` are numeric (otherwise, an LP is solved to evaluate the max of two numbers!)

A more complex example

- $f(x) = x + x^{1.5} + x^{2.5}$, with $\mathbf{dom}\, f = \mathbf{R}_+$, is a convex, monotone increasing function
- its inverse $g = f^{-1}$ is concave, monotone increasing, with $\mathbf{dom}\, g = \mathbf{R}_+$
- there is no closed form expression for g
- $g(y)$ is optimal value of problem

$$\begin{array}{ll} \text{maximize} & t \\ \text{subject to} & t_+ + t_+^{1.5} + t_+^{2.5} \leq y \end{array}$$

(for $y < 0$, this problem is infeasible, so optimal value is $-\infty$)

- implement as

```
function cvx_optval = g(y)
cvx_begin
    variable t;
    maximize(t)
    subject to
        pos(t) + pow_pos(t, 1.5) + pow_pos(t, 2.5) <= y;
cvx_end
```

- use it as an ordinary function, as in `g(14.3)`, or within CVX as a concave function:

```
cvx_begin
    variables x y;
    minimize(quad_over_lin(x, y) + 4*x + 5*y)
    subject to
        g(x) + 2*g(y) >= 2;
cvx_end
```

Example

- optimal value of LP

$$f(c) = \inf\{c^T x \mid Ax \preceq b\}$$

is concave function of c

- by duality (assuming feasibility of $Ax \preceq b$) we have

$$f(c) = \sup\{-\lambda^T b \mid A^T\lambda + c = 0,\ \lambda \succeq 0\}$$

- define f in CVX as

```
function cvx_optval = lp_opt_val(A,b,c)
cvx_begin
    variable lambda(length(b));
    maximize(-lambda'*b);
    subject to
        A'*lambda + c == 0; lambda >= 0;
cvx_end
```

- in `lp_opt_val(A,b,c)` `A`, `b` must be constant; `c` can be affine

CVX hints/warnings

- watch out for = (assignment) versus == (equality constraint)
- `X >= 0`, with matrix `X`, is an elementwise inequality
- `X >= semidefinite(n)` means: `X` is elementwise larger than some positive semidefinite matrix (which is likely not what you want)
- writing `subject to` is unnecessary (but can look nicer)
- many problems traditionally stated using convex quadratic forms can posed as norm problems (which can have better numerical properties):

  `x'*P*x <= 1` can be replaced with `norm(chol(P)*x) <= 1`