

Lecture 2

Qiong Wang

Formulation

Cash Flow and
Financing
Management

MAD-based
Portfolio
Management

Software

Lecture 2

Linear Programming: Examples, Formulations, Software

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Linear Programming (LP) in Standard Form

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$$\begin{array}{ll}\max_{x_1, \dots, x_n} & \{c_1x_1 + \dots + c_nx_n\} \\ \text{subject to} & a_{11}x_1 + \dots + a_{1n}x_n \leq b_1, \\ & \dots\dots\dots \\ & a_{k1}x_1 + \dots + a_{kn}x_n \leq b_k, \\ & x_1 \geq 0, \dots, x_n \geq 0.\end{array}$$

- all decision variables take non-negative real values;
- the objective is to maximize a linear function of decision variables;
- all constraints are linear inequalities of decision variables;
variables are on the LHS and the constant is on the RHS
LHS \leq RHS.

Corporate Financing Problem

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resort
↓

short-term cash flow:

Month	Jan	Feb	Mar	Apr	May	Jun
Net cash flow	-150	-100	200	-200	-50	300

accumulated balance:

Month	Jan	Feb	Mar	Apr	May	Jun
cash balance	-150	-250	-50	-250	-300	0

outside financing is needed: credit line or commercial paper.

Short-term Financing: Credit Line

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r : interest rate,

L : limit

month	balance	interest	net change
1	x_1		x_1
2	x_2	rx_1	$x_2 - x_1$
...
t	x_t	rx_{t-1}	$x_t - x_{t-1}$
...

- $x_t - x_{t-1} > 0$: borrow, more cash and interest payment
- $x_t - x_{t-1} < 0$: return, less cash and interest payment.
- creditline limit: $x_t \leq L$ for all t .

Short-term Financing: Commercial Papers

Not paying interest every month
but we get discount

Promissory note	
For value received, the undersigned promises to pay to the order of BancZone, Inc.	
the sum of:	*****Ten-Thousand and no/100 Dollars***** (\$10,000.00)
Along with annual interest of 8% on the unpaid balance. This note shall mature and be payable, along with accrued interest, on June 30, 20X8.	
<u>January 1, 20X8</u> Issue Date	<u>Olivia Zavala</u> Maker signature

- issuing date (τ_i): 01/01/2008
- amount (y_i): \$ 10,000
- maturity date (m_i): 06/30/2008
- interest rate (δ_i): 8%

Cash Position

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short-term, cash flow: f_t ($t = 1, \dots, T$).

- start from a "clean slate", the net cash position in month 1

$$z_1 = x_1 + \sum_{i:\tau_i=1} y_i + f_1,$$

bank (pointing to x_1)
interest rate once debt (pointing to \sum)
initial (pointing to x_1)

- in month 2,

$$z_2 = z_1 + (x_2 - x_1) - rx_1 + \sum_{i:\tau_i=2} y_i - \sum_{i:m_i=2} (1 + \delta_i)y_i + f_2,$$

change (under $x_2 - x_1$)
2nd month (under $\sum_{i:\tau_i=2}$)
interest rate once debt (pointing to $-rx_1$)
issue commercial paper (pointing to $\sum_{i:m_i=2}$)
nominal value (under $(1 + \delta_i)y_i$)
opening income cost (pointing to f_2)

- similarly, in any other month t ($z_t \geq 0$ for all t to avoid bankruptcy).

$$z_t = z_{t-1} + (x_t - x_{t-1}) - rx_{t-1} + \sum_{i:\tau_i=t} y_i - \sum_{i:m_i=t} (1 + \delta_i)y_i + f_t.$$

pay all my credit card debt (pointing to $-rx_{t-1}$)

- the net value in the end ($x_T = 0$):

$$V = z_T - \sum_{i:m_i>T} (1 + \delta_i)y_i.$$

pay all my credit card debt (pointing to $-$)

Linear Programming Formulation

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$$\max_{x_t, y_i, z_t, V} \{V\}$$

subject to:

$$x_1 + \sum_{i: \tau_i=1} y_i - z_1 = -f_1,$$

$$\downarrow$$
$$\boxed{z_{t-1}} + x_t - (1+r)x_{t-1} + \sum_{i: \tau_i=t} y_i - \sum_{i: m_i=t} (1+\delta_i)y_i - z_t = -f_t, \quad t = 2, \dots, T$$

$$V = z_T - \sum_{i: m_i > T} (1+\delta_i)y_i$$

$$x_T = 0, \quad x_t \leq L, \quad x_t \geq 0, \quad y_i \geq 0, \quad z_t \geq 0, \quad t = 1, \dots, T$$

if the surplus cash also generates interest income with rate r' , then:

replace $\underline{z_{t-1}}$ with $(1+r')z_{t-1}$, $t = 1, \dots, T$ in the above.

Handwritten notes:
- r' is account separate income rate
- r is interest rate
- $r' \leq r$ (boxed)
- No arbitrage \rightarrow $r' \leq r$

Example (C&T)

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Month	Jan	Feb	Mar	Apr	May	Jun
cash flow	-150	-100	200	-200	-50	300

credit line: interest $r = 1\%$ per month, limit, $L = 100$;

commercial paper ($i = 1, 2, 3, (\tau_i, m_i, \delta_i)$): (1, 4, 2%), (2, 5, 2%), (3, 6, 2%).

surplus cash generates an income of 0.3% per month

$$\begin{aligned}
 & \max_{x_t, y_i, z_t, V} \{V\} \quad (\text{in this case, } V = z_6) \\
 \text{subject to: } & x_1 + y_1 - z_1 = 150 \\
 & 1.003z_1 + x_2 + y_2 - \underbrace{1.01x_1}_{\substack{\text{credit line} \\ \text{to } \Theta \text{ of } \text{interest}}} - z_2 = 100, \\
 & 1.003z_2 + x_3 + y_3 - 1.01x_2 - z_3 = -200, \\
 & 1.003z_3 + x_4 - 1.01x_3 - 1.02y_1 - z_4 = 200 \\
 & 1.003z_4 + x_5 - 1.01x_4 - 1.02y_2 - z_5 = 50 \\
 & 1.003z_5 - 1.01x_5 - 1.02y_3 - V = -300 \\
 & x_t \leq 100, \quad x_t \geq 0 \quad y_i \geq 0 \quad z_t \geq 0, \quad i = 1, 2, 3, t = 1, \dots, 6.
 \end{aligned}$$

Related Problem: Financing Long-term Project

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- project lasts from year 1 to year T , expenses L_t ($t = 1, \dots, T$).
- a set of bonds ($i = 1, \dots, n$) available now, face value 100.
price: p_i , coupon rate: c_i , maturity date: m_i
- fund available to cover expenses, the target is to minimize the spending (by using income from the bond).

z_t : cash in year t (z_0 : initial investment, no new cash injection)

x_i : the amount of bond i invested ($i = 1, \dots, n$).

$$\begin{aligned} & \min_{x_i, z_t} \left\{ z_0 + \sum_{i=1}^n p_i x_i \right\} \\ \text{subject to: } & z_{t-1} + \sum_{i: m_i \geq t} c_i x_i + \sum_{i: m_i = t} 100 x_i - z_t = L_t \\ & x_i \geq 0 \ (i = 1, n), \quad z_t \geq 0 \ (t = 0, \dots, T). \end{aligned}$$

A Portfolio Management Problem

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n assets with historical returns $R_i(t)$ ($1 \leq i \leq n$), $t = 1, \dots, T$.

estimated rate of return of each asset

$$r_i = \frac{R_i(1) + \dots + R_i(T)}{T}, \quad 1 \leq i \leq n.$$

Problem: invest a fixed investment budget into these assets.

- decision: x_i be % invested in asset i ($i = 1, \dots, n$),
- objective:

$$\max_{x_1, \dots, x_n} \{r_1 x_1 + r_2 x_2 + \dots + r_n x_n\}$$

- constraints:

$$x_1 + x_2 + \dots + x_n \leq 1, \quad \text{and} \quad x_1 \geq 0, \quad x_2 \geq 0, \dots, \quad x_n \geq 0.$$

and more importantly

$$\text{Risk} \leq \text{some threshold}$$

MAD as a Risk Measure

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- average return over T years: $r_1x_1 + \dots + r_nx_n$
- actual return in year t : $x_1R_1(t) + x_2R_2(t) + \dots + x_nR_n(t)$, where

$$\frac{1}{T} \sum_{t=1}^T \left(\sum_{i=1}^n R_i(t)x_i \right) = \sum_{i=1}^n r_ix_i$$

i.e.,

$$\frac{1}{T} \sum_{t=1}^T \left(\sum_{i=1}^n (R_i(t) - r_i)x_i \right) = 0$$

yearly deviation from the mean

$$\sum_{i=1}^n (R_i(t) - r_i)x_i \quad t = 1, \dots, T.$$

- Mean Absolute Deviation (MAD) as the risk measure:

$$\frac{1}{T} \sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i)x_i \right|$$

Mean-Risk Model

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let \bar{m} be the upper bound of the MAD that you can accept:

$$\begin{aligned} & \max_{x_1, \dots, x_n} \{r_1 x_1 + \dots + r_n x_n\} \\ \text{subject to} \quad & x_1 + x_2 + \dots + x_n \leq 1, \\ & \frac{1}{T} \sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i) x_i \right| \leq \bar{m}. \\ & x_1 \geq 0, x_2 \geq 0, \dots, x_n \geq 0. \end{aligned}$$

issue:

not a linear function

$$\sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i) x_i \right|$$


is not an linear function of x_1, \dots, x_n .

but, in this case, we can transform the problem and solve it as a LP.

Transformation Technique

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a is a number and x is a variable, let

$$x \geq a \quad \text{and} \quad x \geq -a.$$

then

$$\left. \begin{array}{ll} a \geq 0 & \longrightarrow x \geq a \geq -a. \\ a \leq 0 & \longrightarrow x \geq -a \geq a. \end{array} \right\} \longrightarrow x \geq |a|$$

similarly, introduce variables z_t ($t = 1, \dots, T$), and let

$$z_t \geq \sum_{i=1}^n (R_i(t) - r_i) x_i$$

$$\text{and } z_t \geq -\sum_{i=1}^n (R_i(t) - r_i) x_i.$$

add 2 linear
constraint

then

$$z_t \geq \left| \sum_{i=1}^n (R_i(t) - r_i) x_i \right| \quad t = 1, \dots, T.$$

equivalent

Solving the Problem as an LP

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subject to:

$$\max_{\hat{x}_1, \dots, \hat{x}_n} \{r_1 \hat{x}_1 + \dots + r_n \hat{x}_n\}$$

$$\hat{x}_1 + \dots + \hat{x}_n \leq 1,$$

$$\hat{x}_1 \geq 0, \dots, \hat{x}_n \geq 0,$$

$$\frac{1}{T} \sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \right| \leq \bar{m},$$

$$\frac{1}{T} (z_1 + \dots + z_T) \leq \bar{m},$$

$$z_t \geq \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \quad (t = 1, \dots, T),$$

$$z_t \geq - \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \quad (t = 1, \dots, T).$$

This is an LP, and we will show it is equivalent to the original problem by making two comparisons.

Comparison 1

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$$\Pi_1 = \max_{x_1, \dots, x_n} \{r_1 x_1 + \dots + r_n x_n\}$$

$$\sum_{i=1}^n x_i \leq 1, \quad x_1 \geq 0, \dots, x_n \geq 0,$$

$$\frac{1}{T} \sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i) x_i \right| \leq \bar{m}.$$

$$\Pi_2 = \max_{\hat{x}_1, \dots, \hat{x}_n} \{r_1 \hat{x}_1 + \dots + r_n \hat{x}_n\}$$

$$\sum_{i=1}^n \hat{x}_i \leq 1, \quad \hat{x}_1 \geq 0, \dots, \hat{x}_n \geq 0,$$

$$\frac{1}{T} (z_1 + \dots + z_T) \leq \bar{m},$$

$$z_t \geq \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \quad (t = 1, \dots, T),$$

$$z_t \geq - \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \quad (t = 1, \dots, T).$$

If (x_1^*, \dots, x_n^*) is the optimal solution to problem 1, then

$$\hat{x}_1 = x_1^*, \dots, \hat{x}_n = x_n^* \quad z_t = \left| \sum_{i=1}^n (R_i(t) - r_i) x_i^* \right| \quad (t = 1, \dots, T)$$

is a solution to problem 2, so $\Pi_1 \leq \Pi_2$.

Comparison 2

non-linear



$$\Pi_1 = \max_{x_1, \dots, x_n} \{r_1 x_1 + \dots + r_n x_n\}$$

$$\sum_{i=1}^n x_i \leq 1, \quad x_1 \geq 0, \dots, x_n \geq 0,$$

$$\frac{1}{T} \sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i) x_i \right| \leq \bar{m}.$$

linear problem



$$\Pi_2 = \max_{\hat{x}_1, \dots, \hat{x}_n} \{r_1 \hat{x}_1 + \dots + r_n \hat{x}_n\}$$

$$\sum_{i=1}^n \hat{x}_i \leq 1, \quad \hat{x}_1 \geq 0, \dots, \hat{x}_n \geq 0,$$

$$\frac{1}{T} (z_1 + \dots + z_T) \leq \bar{m},$$

$$z_t \geq \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \quad (t = 1, \dots, T),$$

$$z_t \geq - \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i \quad (t = 1, \dots, T).$$

If $(\hat{x}_1^*, \dots, \hat{x}_n^*, z_1^*, \dots, z_T^*)$ is the optimal solution to problem 2, then

$$\frac{1}{T} \sum_{t=1}^T \left| \sum_{i=1}^n (R_i(t) - r_i) \hat{x}_i^* \right| \leq \frac{1}{T} \sum_{t=1}^T z_t^* \leq \bar{m},$$

so $(\hat{x}_1^*, \dots, \hat{x}_n^*)$ is a solution to problem 1, and $\Pi_1 \geq \Pi_2$.

Optimization Solver and Modeling Language

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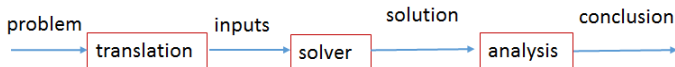
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LP solvers: avoid repetitive developments and use best expertise available.
we will use gurobi (<https://www.gurobi.com/>)

AMPL: a modeling language that facilitates translation and analysis

- teaching copy (incl. gurobi for Windows or MacOS) on Canvas.
- online resources: <http://ampl.com/>
- book: <http://ampl.com/resources/the-ampl-book/chapter-downloads/>

Using AMPL

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teaching copy in “software” folder on Canvas course site, expires on Dec 31.

installation guide:

<https://ampl.com/try-ampl/ampl-for-courses/ampl-course-install/>

Windows: download ampl_mswin64 from Canvas

- extract files to a program folder (e.g., you may named the folder ampl).
- create a user folder for your files and programs.
- create an ampl program and store it in the user folder.
- locate ampl.exe or amplide.exe and run.

Mac OS X: download ampl_macos64, click ampl and then amplide. If amplide.exe does not run because it is not from Mac App store (google to find a solution):

- macOS Catalina and macOS Mojave:
 - 1 System Preferences > Security & Privacy,
 - 2 under the General tab. Click Open Anyway to confirm your intent to open or install the app.
 - 3 you can open it in the future by double-clicking it.
- older macOS: control-click the program icon and choose open.
- if it says the file is damaged, reboot the machine.

Problem Example

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A fund wants to allocate no more than \$1m into two bonds:

- corporate bond: yield 4%, 3-year maturity, and rating A (score 2).
- government bond: yield 3%, 4-year maturity, and rating Aaa (score 1).

Question: how to maximize the yield, while keeping the average maturity below 3.6 years and the rating score no more than 1.2.

LP Formulation:

x_1 : investment in corporate bond,

x_2 : investment in government bond.

$$\begin{array}{ll}\max_{x_1, x_2} & \{4x_1 + 3x_2\} \\ \text{subject to:} & 3x_1 + 4x_2 \leq 3.6, \\ & 2x_1 + x_2 \leq 1.2, \\ & x_1 + x_2 \leq 1, \\ & x_1 \geq 0, x_2 \geq 0.\end{array}$$

Example: Direct Translation

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model (translate into a model file)

subject to:

$$\begin{aligned} \max_{x_1, x_2} & \{4x_1 + 3x_2\} \\ 3x_1 + 4x_2 & \leq 3.6, \\ 2x_1 + x_2 & \leq 1.2, \\ x_1 + x_2 & \leq 1, \\ x_1 \geq 0, x_2 & \geq 0. \end{aligned}$$

steps:

- 1 reset to start
- 2 set path and load model
- 3 choose solver
- 4 solve
- 5 display outputs

The screenshot shows the AMPL IDE interface. On the left, the 'Current Directory' pane shows the file structure: C:\AMPLcode_Class containing Bondexample_Math.mc, Bondexample.dat, Bondexample.mod, and Bondexample.spt. The main window is split into two panes. The left pane, titled 'Console', shows the AMPL command log: 'ampl: reset;', 'ampl: model Bondexample_Math.mod;', 'ampl: options solver gurobi;', 'ampl: solve;', 'Gurobi 7.0.0: optimal solution; objective 3.12', '3 simplex iterations', 'ampl: display x1,x2;', 'x1 = 0.24', 'x2 = 0.72', and 'ampl:'. The right pane, titled 'Bondexample_Math.mod', shows the model code: '## decision variables', 'var x1 >=0;', 'var x2 >=0;', '##Objective function##', 'maximize total_yield: 4*x1+3*x2;', '##constraints##', 'subject to maturity_limit: 3*x1+4*x2<=3.6;', 'subject to rating_limit: 2*x1+x2<=1.2;', and 'subject to total: x1+x2<=1;'. The 'maturity_limit' and 'rating_limit' constraints are highlighted in blue.

```
AMPL
ampl: reset;
ampl: model Bondexample_Math.mod;
ampl: options solver gurobi;
ampl: solve;
Gurobi 7.0.0: optimal solution; objective 3.12
3 simplex iterations
ampl: display x1,x2;
x1 = 0.24
x2 = 0.72
ampl:

## decision variables
var x1 >=0;
var x2 >=0;

##Objective function##
maximize total_yield: 4*x1+3*x2;

##constraints##
subject to maturity_limit: 3*x1+4*x2<=3.6;
subject to rating_limit: 2*x1+x2<=1.2;
subject to total: x1+x2<=1;
```

Example: Better Implementation, Reusable Model

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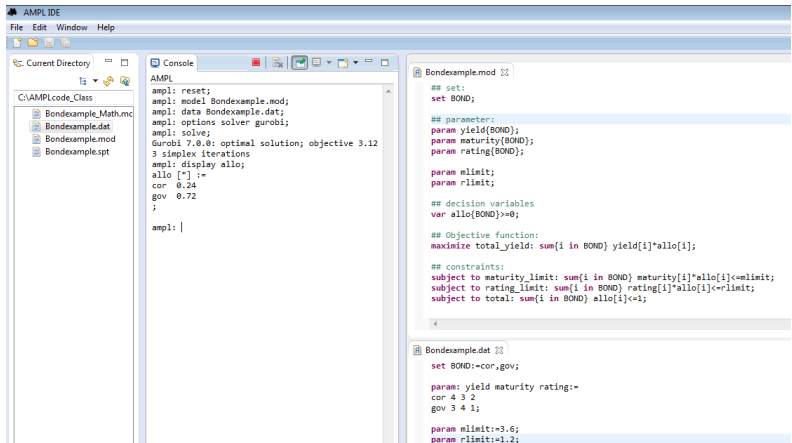
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The screenshot shows the AMPL IDE interface. On the left, the 'Current Directory' pane shows a project structure for 'C:\AMPLcode_Class' containing files: 'Bondexample_Math.mc', 'Bondexample.dat', 'Bondexample.mod', and 'Bondexample.spt'. The main window is split into three panes. The top-left pane shows the AMPL command line with the following code:

```
ampl: reset;  
ampl: model Bondexample.mod;  
ampl: data Bondexample.dat;  
ampl: options solver gurobi;  
ampl: solve;  
Gurobi 7.0.0: optimal solution; objective 3.12  
3 simplex iterations  
ampl: display allo;  
allo [*] :=  
cor 0.24  
gov 0.72  
;  
ampl: |
```

 The top-right pane shows the 'Bondexample.mod' file with the following code:

```
## set:  
set BOND;  
  
## parameter:  
param yield{BOND};  
param maturity{BOND};  
param rating{BOND};  
  
param mlimit;  
param rlimit;  
  
## decision variables  
var allo{BOND}>=0;  
  
## Objective function:  
maximize total_yield: sum{i in BOND} yield[i]*allo[i];  
  
## constraints:  
subject to maturity_limit: sum{i in BOND} maturity[i]*allo[i]<=mlimit;  
subject to rating_limit: sum{i in BOND} rating[i]*allo[i]<=rlimit;  
subject to total: sum{i in BOND} allo[i]<=1;
```

 The bottom-right pane shows the 'Bondexample.dat' file with the following code:

```
set BOND:=cor,gov;  
  
param: yield maturity rating:=  
cor 4 3 2  
gov 3 4 1;  
  
param mlimit:=3.6;  
param rlimit:=1.2;
```

- separate model and data into different files;
- impose structure and naming in the model: set, parameter, variable, obj., and constraints.

Example: Use of Command Script

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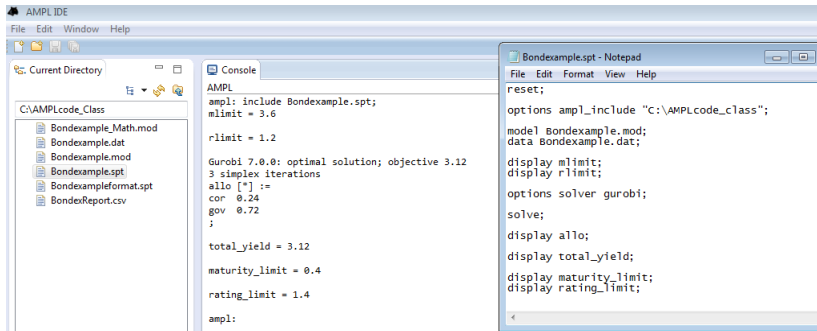
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- set path;
- load model and data files;
- display input parameters;
- choose the solver and solve;
- display outcomes.

What Else Can You Do with a Script

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```

reset;
options ampl_include "C:\AMPLcode_class";
model Bondexample.mod;
data Bondexample.dat;

options solver gurobi;

solve;

printf "\n\n---Optimization Output ----- \n";
printf "opt. obj:\t%.3f\n",total_yield;

printf "----- \n";

printf "\n\n\tmat.\tmscore\tyield\t|opt_allo.\n";

printf "-----|----- \n";
for {i in BOND} {
    printf "%s\t%.2f\t%.2f\t%.2f\t|%.2f\n",
           i,maturity[i],rating[i],yield[i],allo[i];
}

printf ",,Report, \n,allo, mat.,score,yield\n" >Report.csv;
for {i in BOND} {
    printf "%s,%.2f,%.2f,%.2f,%.2f\n",
           i,allo[i], maturity[i],rating[i],yield[i]>Report.csv;
}
printf "----- \n"> Report.csv;
printf "total,%.2f,%.2f,%.2f,%.2f\n", sum{i in BOND} allo[i],
      sum{i in BOND} allo[i]*maturity[i],
      sum{i in BOND} allo[i]*rating[i],
      sum{i in BOND} allo[i]*yield[i] > Report.csv;

```

Screen and File Outputs

Lecture 2

Qiong Wang

Formulation

Cash Flow and
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```
ampl: include Bondexampleformat.spt;  
Gurobi 7.0.0: optimal solution; objective 3.12  
3 simplex iterations
```

```
----Optimization Output -----  
opt. obj:      3.120  
-----
```

	mat.	score	yield	opt_allo.
cor	3.00	2.00	4.00	0.24
gov	4.00	1.00	3.00	0.72

ampl:

Report.csv [Read-Only] - Excel

FILE HOME INSERT PAGE LAY FORMUL DATA REVIEW VIEW ACROBA Wang, Qi...

Paste Font Alignment Number Conditional Formatting Format as Table Cell Styles

Clipboard Styles

A1

	A	B	C	D	E	F	G	H	I
1			Report						
2		allo	mat.	score	yield				
3		cor	0.24	3	2	4			
4		gov	0.72	4	1	3			
5									
6		total	0.96	3.6	1.2	3.12			
7									

Report

READY 100%

What Else Can You Do with a Script: Analysis

Lecture 2

Qiong Wang

Formulation

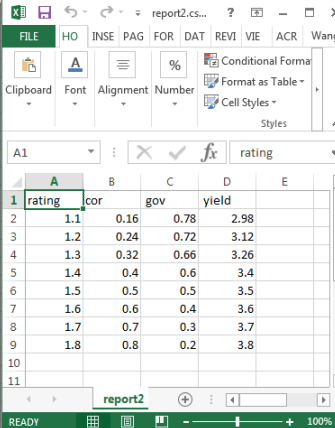
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what happens to the optimal allocation, what is the optimal yield, when the constraint on the rating changes:

```
Bondexampleiterate.spt - Notepad
File Edit Format View Help
reset;
options ampl_include "C:\AMPLcode_class";
model Bondexample.mod;
data Bondexample.dat;
options solver gurobi;
printf "rating,cor, gov, yield\n" > Report2.csv;
for{r in 1..8}{
    let rlimit:=1+0.1*r;
    solve;
    printf "%0.2f,%0.2f,%0.2f,%0.2f\n",
           rlimit,allo["cor"],allo["gov"],total_yield
           >Report2.csv
}
```



	A	B	C	D	E
1	rating	cor	gov	yield	
2	1.1	0.16	0.78	2.98	
3	1.2	0.24	0.72	3.12	
4	1.3	0.32	0.66	3.26	
5	1.4	0.4	0.6	3.4	
6	1.5	0.5	0.5	3.5	
7	1.6	0.6	0.4	3.6	
8	1.7	0.7	0.3	3.7	
9	1.8	0.8	0.2	3.8	
10					
11					