Mathematical Programming

especially Integer Linear Programming and Mixed Integer Programming
Transportation Problem in ECLiPSe

- Vars = [A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3, C4];
- Vars :: 0.0..inf, Can’t recover transportation costs by sending negative amounts
- A1 + A2 + A3 + A4 $\leq 500$, % supply constraints
- B1 + B2 + B3 + B4 $\leq 300$, 
- C1 + C2 + C3 + C4 $\leq 400$, Production capacity of producer “C”
- A1 + B1 + C1 $= 200$, % demand constraints
- A2 + B2 + C2 $= 400$,
- A3 + B3 + C3 $= 300$,
- A4 + B4 + C4 $= 100$, Total amount that must be sent to consumer “4”
- optimize(min(10*A1 + 8*A2 + 5*A3 + 9*A4 + 7*B1 + 5*B2 + 5*B3 + 3*B4 + 11*C1 + 10*C2 + 8*C3 + 7*C4), Cost).

example adapted from ECLiPSe website
Mathematical Programming in General

- Here are some variables:
  Vars = [A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3, C4];

- And some hard constraints on them:
  Vars :: 0.0..inf,
  A1 + A2 + A3 + A4 $<=$ 500,  % supply constraints
  B1 + B2 + B3 + B4 $<=$ 300,
  C1 + C2 + C3 + C4 $<=$ 400,
  A1 + B1 + C1 $=$ 200,  % demand constraints
  A2 + B2 + C2 $=$ 400,
  A3 + B3 + C3 $=$ 300,
  A4 + B4 + C4 $=$ 100,

- Find a satisfying assignment that makes this objective function as large or small as possible:
  10*A1 + 8*A2 + 5*A3 + 9*A4 + 7*B1 + 5*B2 + 5*B3 + 3*B4 +
  11*C1 + 10*C2 + 8*C3 + 7*C4
Mathematical Programming in General

- Here are some variables:

- And some hard constraints on them:

**What kind of constraints?**

- Find a satisfying assignment that makes this objective function as large or small as possible:

**What kind of function?**
Types of Mathematical Programming
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## Linear Programming in 2 dimensions

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2 variables: feasible region is a convex polygon

boundary of feasible region comes from the constraints

image adapted from Keely L. Croxton
## Linear Programming in $n$ dimensions

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3 variables: feasible region is a convex polyhedron

In general case of $n$ dimensions, the word is polytope

(n-1)-dimensional facet, imposed by a linear constraint that is a full (n-1)-dim hyperplane

Image adapted from Keely L. Croxton
### Linear Programming in 2 dimensions

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“level sets” of the objective $x+y$ (sets where it takes a certain value)

![Graphs](image)

$x+y = 4$
$x+y = 5$
$x+y = 6$
$x+y = 7$

images adapted from Keely L. Croxton
### Linear Programming in $n$ dimensions

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If an LP optimum is finite, it can always be achieved at a corner ("vertex") of the feasible region.

(Can there be infinite solutions? Multiple solutions?)

Here, the level set is a plane (in general, a hyperplane).

Image from Keely L. Croxton
Simplex Method for Solving an LP

At every step, move to an adjacent vertex that improves the objective.
### Integer Linear Programming (ILP)

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Function to maximize: \( f(x, y) = 6 \cdot x + 5 \cdot y \)

Optimum LP solution \((x, y) = (2.8, 3.3)\)

Pareto optima: \((0.4), (2.3), (3.2), (4, 1)\)

Optimum ILP solution \((x, y) = (4, 1)\)

- Round to nearest int \((3,3)\)?
  - No, infeasible.

- Round to nearest feasible int \((2,3)\) or \((3,2)\)?
  - No, suboptimal.

- Round to nearest integer vertex \((0,4)\)?
  - No, suboptimal.

Image adapted from Jop Sibeyn
# Mixed Integer Programming (MIP)

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We'll be studying MIP solvers.

SCIP mainly does MIP though it goes a bit farther.

$x$ still integer but $y$ is now real
Quadratic Programming

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Solution no longer at a vertex

level sets of $x^2 + y^2$ (try to minimize)

level sets of $(x-2)^2 + (y-2)^2$ (try to minimize)

same, but maximize (no longer convex)
Quadratic Programming

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Note: On previous slide, we saw that the level sets of our quadratic objective $x^2+y^2$ were circles.

In general (in 2 dimensions), the level sets of a quadratic function will be conic sections: ellipses, parabolae, hyperbolae. E.g., $x^2-y^2$ gives a hyperbola.

The n-dimensional generalizations are called **quadrics**.

Reason, if you're curious: The level set is $Ax^2 + Bxy + Cy^2 + Dx + Ey + F = \text{const}$
Equivalently, $Ax^2 + Bxy + Cy^2 = -Dx -Ey + (\text{const} - F)$
Equivalently, $(x,y)$ is in set if $\exists z$ with $z = Ax^2 + Bxy + Cy^2$ and $z = -Dx -Ey + (\text{const} - F)$
Thus, consider all $(x,y,z)$ points where a **right cone** intersects a plane
### Semidefinite Programming

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## Quadratically Constrained Programming

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Linear objective in this case, so level sets are again hyperplanes, but optimum is not at a vertex.
## Convex Programming

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Non-convexity is hard because it leads to disjunctive choices in optimization (hence backtracking search).

- Infeasible in middle of line: which way to go?
- Objective too large in middle of line: which way to go?
**Convex Programming**

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**Can minimize a convex function by methods such as gradient descent, conjugate gradient, or (for non-differentiable functions) Powell’s method or subgradient descent. No local optimum problem.**

Here we want to generalize to minimization within a convex region. **Still no local optimum problem.** Can use subgradient or interior point methods, etc.

**Note:** If instead you want to maximize within a convex region, the solution is at least known to be on the boundary, if the region is compact (i.e., bounded).
## Nonlinear Programming

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Non-convexity is hard because it leads to disjunctive choices in optimization.

Here in practice one often falls back on methods like simulated annealing.

To get an exact solution, you can try backtracking search methods that recursively divide up the space into regions.

*(Branch-and-bound, if you can compute decent optimistic bounds on the best solution within a region, e.g., by linear approximations.)*
## Types of Mathematical Programming

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Lots of software available for various kinds of math programming!

Huge amounts of effort making it smart, correct, and fast - use it!

See the NEOS Wiki, the Decision Tree for Optimization Software, and the COIN-OR open-source consortium.
## Terminology

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<th>Math Programming</th>
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Linear Programming in ZIMPL
Formal Notation of Linear Programming

- $n$ variables $x_1, x_2, \ldots, x_n$
- max or min objective $c_1x_1 + c_2x_2 + \ldots + c_nx_n$
- $m$ linear inequality and equality constraints

\[
\begin{align*}
    a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n & \leq b_1 \\
    a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n & = b_2 \\
    \vdots & \\
    a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n & \geq b_m
\end{align*}
\]

Note: if a constraint refers to only a few of the vars, its other coefficients will be 0.
Formal Notation of Linear Programming

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\end{align*}
\]

- Can we simplify \(\text{(much as we simplified SAT to CNF-SAT)}\)?
Formal Notation of Linear Programming

- **n** variables \( x_1, x_2, \ldots, x_n \)
- objective: \( \max \ \vec{c} \cdot \vec{x} \)
- **m** linear inequality constraints

\[
A \vec{x} \leq \vec{b}
\]

(where “\( \leq \)” means that \( \forall 1 \leq i \leq m \) \( (A \vec{x})_i \leq b_i \))

- **Now we can use this concise matrix notation**
Formal Notation of Linear Programming

- **n** variables \( x_1, x_2, \ldots, x_n \)
- **objective**: max \( \vec{c} \cdot \vec{x} \)
- **m** linear inequality constraints

\[
A\vec{x} \leq \vec{b}
\]

(where “\( \leq \)” means that (\( \forall 1 \leq i \leq m \)) \((A\vec{x})_i \leq b_i\))

- Some LP folks also assume constraint \( \vec{x} \geq 0 \)
  - What if you want to allow \( x_3 < 0 \)? Just replace \( x_3 \) everywhere with \((x_{n+1} - x_{n+2})\) where \( x_{n+1}, x_{n+2} \) are new variables \( \geq 0 \).
  - Then solver can pick \( x_{n+1}, x_{n+2} \) to have either pos or neg diff.
Strict inequalities?

- \( n \) variables \( x_1, x_2, \ldots, x_n \)
- max or min objective \( c_1 x_1 + c_2 x_2 + \ldots + c_n x_n \)
- \( m \) linear inequality and equality constraints

\[
\begin{align*}
a_{11} x_1 + a_{12} x_2 + \cdots + a_{1n} x_n & \leq b_1 \\
a_{21} x_1 + a_{22} x_2 + \cdots + a_{2n} x_n & = b_2 \\
& \vdots \\
a_{m1} x_1 + a_{m2} x_2 + \cdots + a_{mn} x_n & \geq b_m
\end{align*}
\]

How about using strict > or <?
But then you could say “min \( x_1 \) subject to \( x_1 > 0 \).”
No well-defined solution, so can’t allow this.
Instead, approximate \( x > y \) by \( x \geq y + 0.001 \).
What little language and solver should we use?
Quite a few options …

- Our little language for this course is **ZIMPL** (Koch 2004)
  - A free and extended dialect of **AMPL** = “A Mathematical Programming Language” (Fourer, Gay & Kernighan 1990)
  - Compiles into MPS, an unfriendly punch-card like format accepted by virtually all solvers

- Our solver for mixed-integer programming is **SCIP** (open source)
  - Our version of SCIP will
    1. read a ZIMPL file (*.zpl)
    2. compile it to MPS
    3. solve using its own MIP methods
      - which in turn call an LP solver as a subroutine
        - our version of SCIP calls **CLP** (part of the COIN-OR effort)
Transportation Problem in ECLiPSe

- Vars = [A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3, C4];
- Vars :: 0.0..inf, Can’t recover transportation costs by sending negative amounts

- A1 + A2 + A3 + A4 $\leq 500$, % supply constraints
- B1 + B2 + B3 + B4 $\leq 300$,
- C1 + C2 + C3 + C4 $\leq 400$, Production capacity of producer “C”

- A1 + B1 + C1 $= 200$, % demand constraints
- A2 + B2 + C2 $= 400$,
- A3 + B3 + C3 $= 300$,
- A4 + B4 + C4 $= 100$, Total amount that must be sent to consumer “4”
- optimize(min(10*A1 + 8*A2 + 5*A3 + 9*A4 + 7*B1 + 5*B2 + 5*B3 + 3*B4 + 11*C1 + 10*C2 + 8*C3 + 7*C4), Cost).

Amount that producer “C” sends to consumer “4”

Satisfiable?

Transport cost per unit

example adapted from ECLiPSe website
Transportation Problem in ZIMPL

- var a1; var a2; var a3; var a4;
- var b1; var b2; var b3; var b4;
- var c1; var c2; var c3; var c4;

\[\text{supply}_a: a1 + a2 + a3 + a4 \leq 500;\]
\[\text{supply}_b: b1 + b2 + b3 + b4 \leq 300;\]
\[\text{supply}_c: c1 + c2 + c3 + c4 \leq 400;\]

\[\text{demand}_1: a1 + b1 + c1 = 200;\]
\[\text{demand}_2: a2 + b2 + c2 = 400;\]
\[\text{demand}_3: a3 + b3 + c3 = 300;\]
\[\text{demand}_4: a4 + b4 + c4 = 100;\]

\[\text{minimize cost:} \quad 10a1 + 8a2 + 5a3 + 9a4 + 7b1 + 5b2 + 5b3 + 3b4 + 11c1 + 10c2 + 8c3 + 7c4;\]

Variables are assumed real and \(\geq 0\) unless declared otherwise.

Blue strings are just your names for the constraints and the objective (for documentation and debugging).

Production capacity of producer “C”

Total amount that must be sent to consumer “4”
Transportation Problem in ZIMPL

- set Producer := {1 .. 3};
- set Consumer := {1 to 4};
- var send[Producer*Consumer];

- subto supply_a: sum <c> in Consumer: send[1,c] <= 500;
- subto supply_b: sum <c> in Consumer: send[2,c] <= 300;
- subto supply_c: sum <c> in Consumer: send[3,c] <= 400;

- subto demand_1: sum <p> in Producer: send[p,1] == 200;
- subto demand_2: sum <p> in Producer: send[p,2] == 400;
- subto demand_3: sum <p> in Producer: send[p,3] == 300;
- subto demand_4: sum <p> in Producer: send[p,4] == 100;

Transportation Problem in ZIMPL

- set Producer := {“alice”, “bob”, “carol”};
- set Consumer := {1 to 4};
- var send[Producer*Consumer];

- subto supply_a: sum <c> in Consumer: send[“alice”,c] <= 500;
- subto supply_b: sum <c> in Consumer: send[“bob”,c] <= 300;
- subto supply_c: sum <c> in Consumer: send[“carol”,c] <= 400;

- subto demand_1: sum <p> in Producer: send[p,1] == 200;
- subto demand_2: sum <p> in Producer: send[p,2] == 400;
- subto demand_3: sum <p> in Producer: send[p,3] == 300;
- subto demand_4: sum <p> in Producer: send[p,4] == 100;


Variables are assumed real and >= 0 unless declared otherwise.
Transportation Problem in ZIMPL

- set Producer := {“alice”,“bob”,“carol”};
- set Consumer := {1 to 4};
- var send[Producer*Consumer] >= -10000;
- param supply[Producer] := <"alice"> 500, <"bob"> 300, <"carol"> 400;
- param demand[Consumer] := <1> 200, <2> 400, <3> 300, <4> 100;
- param transport_cost[Producer*Consumer] :=
  |   1,  2,  3,  4 |
  |"alice"  |10,  8,  5,  9 |
  |"bob"     | 7,  5,  5,  3 |
  |"carol"   |11,10,  8,  7 |
- subto supply: forall <p> in Producer:
  (sum <c> in Consumer: send[p,c]) <= supply[p];
- subto demand: forall <c> in Consumer:
  (sum <p> in Producer: send[p,c]) == demand[c];
- minimize cost: sum <p,c> in Producer*Consumer:
  transport_cost[p,c] * send[p,c];

Variables are assumed real and >= 0 unless declared otherwise

unknowns (remark: mustn’t multiply unknowns by each other if you want a linear program)

unknowns

knowns

Collapse similar formulas that differ only in constants by using indexed names for the constants, too ("parameters")
How to Encode Interesting Things in LP (sometimes needs MIP)
Slack variables

- What if transportation problem is UNSAT?
- E.g., total possible supply < total demand

- Relax the constraints. Change
  \[
  \text{subto } \text{demand}_1: a_1 + b_1 + c_1 = 200;
  \]
  to
  \[
  \text{subto } \text{demand}_1: a_1 + b_1 + c_1 \leq 200?
  \]

  No, then we’ll manufacture nothing, and achieve a total cost of 0.
Slack variables

- What if transportation problem is UNSAT?
- E.g., total possible supply < total demand

- Relax the constraints. Change

  \[
  \text{subto demand}_1: a_1 + b_1 + c_1 == 200;
  \]

  to

  \[
  \text{subto demand}_1: a_1 + b_1 + c_1 >= 200 \]

  Obviously doesn’t help UNSAT. But what happens in SAT case?

  Answer: It doesn’t change the solution. Why not?

  Ok, back to our problem ...

- This is typical: the solution will achieve equality on some of your inequality constraints. Reaching equality was what stopped the solver from pushing the objective function to an even better value.

- And == is equivalent to >= and <=. Only one of those will be “active” in a given problem, depending on which way the objective is pushing. Here the <= half doesn’t matter because the objective is essentially trying to make a1+b1+c1 small anyway. The >= half will achieve equality all by itself.
Slack variables

What if transportation problem is UNSAT?
E.g., total possible supply < total demand

Relax the constraints. Change

\[
\text{subto demand}_1: a_1 + b_1 + c_1 == 200; \\
to \\
\text{subto demand}_1: a_1 + b_1 + c_1 + \text{slack}_1 == 200; \quad (\text{or } \geq 200)
\]

Now add a linear term to the objective:

\[
\text{minimize cost: } (\text{sum } <p,c> \text{ in Producer*Consumer:} \\
\text{transport}_\text{cost}[p,c] * \text{send}[p,c]) \\
+ (\text{slack}_1\_\text{cost}) * \text{slack}_1; \\
\text{cost per unit of buying from an outside supplier}
\]
Slack variables

What if transportation problem is UNSAT?
E.g., total possible supply < total demand

Relax the constraints. Change

\[
\text{subto } \text{demand}_1: a1 + b1 + c1 == 200;
\]

to

\[
\text{subto } \text{demand}_1: a1 + b1 + c1 == 200 - \text{slack}_1;
\]

Now add a linear term to the objective:

\[
\text{minimize } \text{cost: } (\text{sum } <p,c> \text{ in Producer*Consumer:} \\
\text{transport\_cost}[p,c] \times \text{send}[p,c]) \\
\text{+ (slack1\_cost) } \times \text{slack1;}
\]

Also useful if we could meet demand but maybe would rather not: trade off transportation cost against cost of not quite meeting demand

Cost per unit of doing without the product
Piecwise linear objective

- What if cost of doing without the product goes up non-linearly?
- It’s pretty bad to be missing 20 units, but we’d make do.
- But missing 60 units is really horrible (more than 3 times as bad) …

We can handle it still by linear programming:

\[
\begin{align*}
\text{subto demand}_1: & \quad a_1 + b_1 + c_1 + \text{slack1} + \text{slack2} + \text{slack3} = 200; \\
\text{subto s1:} & \quad \text{slack1} \leq 20; \quad \# \text{ first 20 units} \\
\text{subto s2:} & \quad \text{slack2} \leq 10; \quad \# \text{ next 10 units (up to 30)} \\
\text{subto s3:} & \quad \text{slack3} \leq 30; \quad \# \text{ next 30 units (up to 60)}
\end{align*}
\]

Now add a linear term to the objective:

\[
\text{minimize cost:} \quad (\text{sum } p,c \text{ in Producer*Consumer:} \\
\quad \text{transport_cost}[p,c] \times \text{send}[p,c])
\]

\[
\quad + (\text{slack1_cost} \times \text{slack1}) + (\text{slack2_cost} \times \text{slack2}) + (\text{slack3_cost} \times \text{slack3})
\]

not too bad \quad worse (per unit) \quad ouch! out of business

so max total slack is 60; could drop this constraint to allow \( \infty \)
Piecewise linear objective

- subto demand_1: a1 + b1 + c1 + slack1 + slack2 + slack3 <= 200;
- subto s1: slack1 <= 20;  # first 20 units
- subto s2: slack2 <= 10;  # next 10 units (up to 30)
- subto s3: slack3 <= 30;  # next 30 units (up to 60)

minimize cost: (sum <p,c> in Producer*Consumer:
    transport_cost[p,c] * send[p,c])
  + (slack1_cost * slack1) + (slack2_cost * slack2) + (slack3_cost * slack3);

Note: Can approximate any continuous function by piecewise linear. In our problem, slack1 <= slack2 <= slack3 (costs get worse).
Piecewise linear objective

- subto demand_1: a1 + b1 + c1 + slack1 + slack2 + slack3 <= 200;
- subto s1: slack1 <= 20;  # first 20 units
- subto s2: slack2 <= 10;  # next 10 units (up to 30)
- subto s3: slack3 <= 30;  # next 30 units (up to 60)

minimize cost: (sum <p,c> in Producer*Consumer:
    transport_cost[p,c] * send[p,c])
    + (slack1_cost * slack1) + (slack2_cost * slack2) + (slack3_cost * slack3);

Note: Can approximate any continuous function by piecewise linear.
In our problem, slack1_cost <= slack2_cost <= slack3_cost
(costs get worse).
It’s actually important that costs get worse. Why?

Answer 1: Otherwise the encoding is wrong!
(If slack2 is cheaper, solver would buy from outside supplier 2 first.)

Answer 2: It ensures that the objective function is convex!
Otherwise too hard for LP; we can’t expect any LP encoding to work.

Therefore: E.g., if costs get progressively cheaper, (e.g., so-called
“economies of scale” – quantity discounts), then you can’t use LP. 😞

How about integer linear programming (ILP)?
Piecewise linear objective

- subto demand_1: a1 + b1 + c1 + slack1 + slack2 + slack3 <= 200;
- subto s1: slack1 <= 20; # first 20 units
- subto s2: slack2 <= 10; # next 10 units (up to 30)
- subto s3: slack3 <= 30; # next 30 units (up to 60)
- minimize cost: (sum <p,c> in Producer*Consumer: 
  transport_cost[p,c] * send[p,c])
  + (slack1_cost * slack1) + (slack2_cost * slack2) + (slack3_cost * slack3);

- Need to ensure that even if the slack_costs are set arbitrarily (any function!), slack1 must reach 20 before we can get the quantity discount by using slack2.
- Use integer linear programming. How?
- var k1 binary; var k2 binary; var k3 binary; # 0-1 ILP
- subto slack1 <= 20*k1; # can only use slack1 if k1==1, not if k1==0
  subto slack2 <= 10*k2;  
  subto slack3 <= 30*k3;
- subto slack1 >= k2*20; # if we use slack2, then slack1 must be fully used
  subto slack2 >= k3*10; # if we use slack3, then slack2 must be fully used

Can drop k1. It really has no effect, since nothing stops it from being 1. Corresponds to the fact that we're always allowed to use slack1.
Piecewise linear objective

- subto demand_1: \( a_1 + b_1 + c_1 + \text{slack}_1 + \text{slack}_2 + \text{slack}_3 \leq 200 \);
- subto s1: \( \text{slack}_1 \leq 20 \); \# first 20 units
- subto s2: \( \text{slack}_2 \leq 10 \); \# next 10 units (up to 30)
- subto s3: \( \text{slack}_3 \leq 30 \); \# next 30 units (up to 60)

minimize cost: (sum \( <p,c> \) in Producer*Consumer:
transport_cost[p,c] * send[p,c])
+ (slack1_cost * slack1) + (slack2_cost * slack2) + (slack3_cost * slack3);

Note: Can approximate any continuous function by piecewise linear.
Divide into convex regions, use ILP to choose region.

slack4_cost is negative
slack5_costs is negative
slack6_cost is negative
so in these regions, prefer to take more slack (if constraints allow)
Image Alignment
Image Alignment

as a transportation problem, via “Earth Mover’s Distance” (Monge, 1781)
Image Alignment

*as a transportation problem, via “Earth Mover’s Distance”* (Monge, 1781)
Image Alignment

as a transportation problem, via “Earth Mover’s Distance” (Monge, 1781)

- param N := 12;  param M := 10;  # dimensions of image
- set X := {0..N-1};  set Y := {0..M-1};
- set P := X*Y;  # points in source image
- set Q := X*Y;  # points in target image
- defnumb norm(x,y) := sqrt(x*x+y*y);
- defnumb dist(<x1,y1>,<x2,y2>) := norm(x1-x2,y1-y2);
- param movecost := 1;
- param delcost := 1000;  param inscost := 1000;
- var move[P*Q];  # amount of earth moved from P to Q
- var del[P];  # amount of earth deleted from P in source image
- var ins[Q];  # amount of earth added at Q in target image
Image Alignment

as a transportation problem, via “Earth Mover’s Distance”  (Monge, 1781)

- defset Neigh := { -1 .. 1 } * { -1 .. 1 } - {<0,0>};

- minimize emd:
  \[
  \text{minimize } \text{emd:} \\
  \left( \sum_{p,q} \text{move}[p,q] \cdot \text{movecost} \cdot \text{dist}(p,q) \right) \\
  + \left( \sum_p \text{del}[p] \cdot \text{delcost} \right) + \left( \sum_q \text{ins}[q] \cdot \text{inscost} \right);
  \]

- subto source: forall <p> in P:
  \[
  \text{source}[p] = \text{del}[p] + \left( \sum_q \text{move}[p,q] \right);
  \]

- subto target: forall <q> in Q:
  \[
  \text{target}[q] = \text{ins}[q] + \left( \sum_p \text{move}[p,q] \right);
  \]

- subto smoothness: forall <p> in P: forall <q> in Q: forall <d> in Neigh:
  \[
  \text{move}[p,q]/\text{source}[p] \leq 1.01 \cdot \text{move}[p+d,q+d]/\text{source}[p+d]
  \]

constant, so ok for LP (if > 0)

warning: this code takes some liberties with ZIMPL, which is not quite this flexible in handling tuples; a running version would be slightly uglier

don’t have to do it all by moving dirt: if that’s impossible or too expensive, can manufacture/destroy dirt

no longer a standard transportation problem; solution might no longer be integers (even if 1.01 is replaced by 2)
L1 Linear Regression

Given data \((x_1, y_1), (x_1, y_2), \ldots (x_n, y_n)\)

Find a linear function \(y = mx + b\) that approximately predicts each \(y_i\) from its \(x_i\) (why?)

Easy and useful generalization not covered on these slides:
- each \(x_i\) could be a vector (then \(m\) is a vector too and \(mx\) is a dot product)
- each \(y_i\) could be a vector too (then \(mx\) is a matrix and \(mx\) is a matrix multiplication)
L1 Linear Regression

- Given data \((x_1, y_1), (x_1, y_2), \ldots (x_n, y_n)\)
- Find a linear function \(y = mx + b\) that approximately predicts each \(y_i\) from its \(x_i\)
- **Standard “L2” regression:**
  - minimize \(\sum_i (y_i - (mx_i + b))^2\)
  - This is a convex quadratic problem. Can be handled by gradient descent, or more simply by setting the gradient to 0 and solving.
- **“L1” regression:**
  - minimize \(\sum_i |y_i - (mx_i + b)|\), so \(m\) and \(b\) are less distracted by outliers
  - Again convex, but not differentiable, so no gradient!
  - But now it’s a linear problem. Handle by linear programming:
    - subto \(y_i = (mx_i + b) + (u_i - v_i)\);
    - subto \(u_i \geq 0\); subto \(v_i \geq 0\);
    - minimize \(\sum_i (u_i + v_i)\);
More variants on linear regression

- **L1 linear regression:**
  - Minimize \( \sum_i |y_i - (mx_i + b)| \), so m and b are less distracted by outliers
  - Handle by linear programming:
    
    \[
    \text{subto } y_i = (mx_i + b) + (u_i - v_i); \quad \text{subto } u_i \geq 0; \quad \text{subto } v_i \geq 0;
    \]
    
    \[
    \text{minimize } \sum_i (u_i + v_i); \]

- **Quadratic regression:** \( y_i \approx (ax_i^2 + bx_i + c) \)?
  - Answer: Still linear constraints! \( x_i^2 \) is a constant since \( (x_i, y_i) \) is given.

- **L∞ linear regression:** Minimize the maximum residual instead of the total of all residuals?
  - Answer: Minimize \( z \); subto forall \(<i> in I: u_i + v_i \leq z; \)
  - **Remark:** Including max(\( p,q,r \)) in the cost function is easy.
    Just minimize \( z \) subject to \( p \leq z, q \leq z, r \leq z \). Keeps all of them small.
  - **But:** Including min(\( p,q,r \)) is hard! Choice about which one to keep small.
    - Need ILP. Binary \( a,b,c \) with \( a+b+c = 1 \). Choice of \((1,0,0),(0,1,0),(0,0,1)\).
    - Now what? First try: min \( ap+bq+cr \). But \( ap \) is quadratic, oops!
    - Instead: use lots of slack on unenforced constraints. Min \( z \) subj. to \( p \leq z + M(1-a), q \leq z + M(1-b), r \leq z + M(1-c), \) where \( M \) is large constant.
CNF-SAT (using binary ILP variables)

- We just said “a+b+c==1” for “exactly one” (sort of like XOR).
- Can we do any SAT problem?
  - If so, an ILP solver can handle SAT … and more.

Example: \((A \lor B \lor \neg C) \land (D \lor \neg E)\)

- SAT version:
  - constraints: \((a+b+(1-c)) \geq 1, \ (d+(1-e)) \geq 1\)
  - objective: none needed, except to break ties

- MAX-SAT version:
  - constraints: \((a+b+(1-c)) - u_1 \geq 1, \ (d+(1-e)) + u_2 \geq 1\)
  - objective: minimize \(c_1*u_1 + c_2*u_2\)
    - where \(c_1\) is the cost of violating constraint 1, etc.
Non-clausal SAT (again using 0-1 ILP)

- If A is a [boolean] variable, then A and ~A are “literal” formulas.
- If F and G are formulas, then so are
  - F ^ G (“F and G”)
  - F v G (“F or G”)
  - F \rightarrow G (“If F then G”; “F implies G”)
  - F \leftrightarrow G (“F if and only if G”; “F is equivalent to G”)
  - F xor G (“F or G but not both”; “F differs from G”)
  - ~F (“not F”)

- If we are given a non-clausal formula, easy to set up as ILP using auxiliary variables.
Non-clausal SAT (again using 0-1 ILP)

- If we are given a non-CNF constraint, easy to set up as ILP using auxiliary variables.

\[(A \land B) \lor (A \land \neg(C \land (D \lor E)))\]

\[Q \geq D; \quad Q \geq E; \quad Q \leq D+E\]
\[R \leq C; \quad R \leq Q; \quad R \leq C+Q-1\]
\[S \leq A; \quad S \leq (1-R); \quad S \geq A+(1-R)-1\]
\[T \geq P; \quad T \geq S; \quad T \leq P+S\]

Finally, require \(T=1\).
Or for a soft constraint, add \(cost \times (1-T)\) to the minimization objective.

Note: Introducing one intermediate variable per subexpression can be used in place of the CNF conversion tricks we learned long ago. Either approach would work in either setting. This approach has only \textit{linear} blowup in formula size! (But it introduces more variables.)
MAX-SAT example: Linear Ordering Problem

- Arrange these archaeological artifacts or fossils along a timeline
- Arrange a program’s functions in a sequence so that callers tend to be above callees
- Poll humans based on pairwise preferences: Then sort the political candidates or policy options or acoustic stimuli into a global order
- In short: Sorting with a flaky comparison function
  - might not be asymmetric, transitive, etc.
  - can be weighted
    - the comparison “a < b” isn’t boolean, but real
    - strongly positive/negative if we strongly want a to precede/follow b
  - maximize the sum of preferences
  - NP-hard
MAX-SAT example: Linear Ordering Problem

- set X := { 1 … 50 };  
  \# set of objects to be ordered
- param G[X * X] := read "test.lop" as "<1n, 2n> 3n";

- var LessThan[X * X] binary;
- maximize goal: sum <x,y> in X * X : G[x,y] * LessThan[x,y];

- subto irreflexive: forall <x> in X: LessThan[x,x] == 0;
- subto antisymmetric_and_total: forall <x,y> in X * X with x < y:  
  LessThan[x,y] + LessThan[y,x] == 1;  
  \# what would <= and => do?
- subto transitive: forall <x,y,z> in X * X * X:  
  \# if x<y and y<z then x<z  
  LessThan[x,z] >= LessThan[x,y] + LessThan[y,z] - 1;

  \# alternatively (get this by adding LessThan[z,x] to both sides)
- \# subto transitive: forall <x,y,z> in X * X * X  
  \# with x < y and x < z and y != z:  
  \# merely prevents redundancy
- \# LessThan[x,y] + LessThan[y,z] + LessThan[z,x] <= 2; \# no cycles

ZIMPL code thanks to Jason Smith
Why isn’t this just SAT all over again?

- Different solution techniques (we’ll compare)
- Much easier to encode “at least 13 of 26”:
  - Remember how we had to do it in pure SAT?
Encoding “at least 13 of 26”  
(without listing all 38,754,732 subsets!)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>...</th>
<th>L</th>
<th>M</th>
<th>...</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>A≥1</td>
<td>A-B≥1</td>
<td>A-C≥1</td>
<td></td>
<td>A-L≥1</td>
<td>A-M≥1</td>
<td></td>
<td>A-Y≥1</td>
<td>A-Z≥1</td>
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<tr>
<td>A-M≥13</td>
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</tbody>
</table>

26 original variables `A` ... `Z`, plus $< 26^2$ new variables such as `A-L≥3`

- SAT formula should require that `A-Z≥13` is true ... and what else?
- yadayada $\wedge A-Z≥13 \wedge (A-Z≥13 \rightarrow (A-Y≥13 \lor (A-Y≥12 \wedge Z))) 
  \wedge (A-Y≥13 \rightarrow (A-X≥13 \lor (A-X≥12 \wedge Y)))) \wedge ...$

one “only if” definitional constraint for each new variable
Why isn’t this just SAT all over again?

- Different solution techniques (we’ll compare)
- Much easier to encode “at least 13 of 26”:
  - \(a+b+c+\ldots+z \geq 13\) (and solver exploits this)
  - Lower bounds on such sums are useful to model requirements
  - Upper bounds on such sums are useful to model limited resources
  - Can include real coefficients (e.g., \(c\) uses up 5.4 of the resource):
    - \(a + 2b + 5.4c + \ldots + 0.3z \geq 13\) (very hard to express with SAT)
    - MAX-SAT allows an overall soft constraint, but not a limit of 13
      (nor a piecewise-linear penalty function for deviations from 13)
- Mixed integer programming combines the power of SAT and disjunction with the power of numeric constraints
  - Even if some variables are boolean, others may be integer or real and constrained by linear equations (“Mixed Integer Programming”)
Logical control of real-valued constraints

- Want $\delta=1$ to force an inequality constraint to turn on:
  (where $\delta$ is a binary variable)

- **Idea:** $\delta=1 \rightarrow a \cdot x \leq b$
- **Implementation:** $a \cdot x \leq b + M(1-\delta)$ where $M$ very large
  - Requires $a \cdot x \leq b + M$ always, so set $M$ to **upper bound** on $a \cdot x - b$

---

- Conversely, want satisfying the constraint to force $\delta=1$:

- **Idea:** $a \cdot x \leq b \rightarrow \delta=1$ or equivalently $\delta=0 \rightarrow a \cdot x > b$
- **Implementation:**
  - approximate by $\delta=0 \rightarrow a \cdot x \geq b + 0.001$
  - implement as $a \cdot x + \text{surplus} \cdot \delta \geq b + 0.001$
  - more precisely $a \cdot x \geq b + 0.001 + (m-0.001) \cdot \delta$ where $m$ very negative
  - Requires $a \cdot x \geq b + m$ always, so set $m$ to **lower bound** on $a \cdot x - b$
Logical control of real-valued constraints

- If some inequalities hold, want to enforce others too.
- ZIMPL doesn’t (yet?) let us write
  - subto foo: \((a.x <= b \text{ and } c.x <= d) \rightarrow (e.x <= f \text{ or } g.x <= h)\)
  but we can manually link these inequalities to binary variables:
    - \(a.x \leq b \rightarrow \delta_1\) implement as on bottom half of previous slide
    - \(c.x \leq d \rightarrow \delta_2\) implement as on bottom half of previous slide
    - \((\delta_1 \text{ and } \delta_2) \rightarrow \delta_3\) implement as \(\delta_3 \geq \delta_1 + \delta_2 - 1\)
    - \(\delta_3 \rightarrow (\delta_4 \text{ or } \delta_5)\) implement as \(\delta_3 \leq \delta_4 + \delta_5\)
    - \(\delta_4 \rightarrow e.x \leq f\) implement as on top half of previous slide
    - \(\delta_5 \rightarrow g.x \leq h\) implement as on top half of previous slide

- Partial shortcut in ZIMPL using “vif … then … else .. end” construction:
  - subto foo1: vif \((\delta_1==0)\) then \(a.x >= b+0.001\) end;
  - subto foo2: vif \((\delta_2==0)\) then \(c.x >= d+0.001\) end;
  - subto foo3: vif ((\(\delta_1==1\) and \(\delta_2==1\)) and not (\(\delta_4==1\) or \(\delta_5==1\)))
    then \(\delta_1 \geq \delta_1 + 1\) end;  
    # i.e., the “vif” condition is impossible
  - subto foo4: vif \((\delta_4==1)\) then \(e.x <= f\) end;
  - subto foo5: vif \((\delta_5==1)\) then \(g.x <= h\) end;
Integer programming beyond 0-1: N-Queens Problem

- param queens := 8;
- set C := {1 .. queens};
- var row[C] integer >= 1 <= queens;

- set Pairs := {<i,j> in C*C with i < j};
- subto alldifferent: forall <i,j> in Pairs: row[i] != row[j];
- subto nodiagonal: forall <i,j> in Pairs: vabs(row[i]-row[j]) != j-i;
- # no line saying what to maximize or minimize

Instead of writing x != y in ZIMPL, or (x-y) != 0, need to write vabs(x-y) >= 1. (if x,y integer; what if they're real?)
This is equivalent to v >= 1 where v is forced (how?) to equal |x-y|.
  v >= x-y, v >= y-x, and add v to the minimization objective.
No, can't be right def of v: LP alone can't define non-convex feasible region.
And it is wrong: this encoding will allow x==y and just choose v=1 anyway!
Correct solution: use ILP. Binary var δ, with δ=0 → v=x-y, δ=1 → v=y-x.
Or more simply, eliminate v: δ=0 → x-y ≥ 1, δ=1 → y-x ≥ 1.

program example from ZIMPL manual
Integer programming beyond 0-1: Allocating Indivisible Objects

- **Airline scheduling**
  (can’t take a fractional number of passengers)

- **Job shop scheduling (like homework 2)**
  (from a set of identical jobs, each machine takes an integer #)

- **Knapsack problems (like homework 4)**

- **Others?**
Harder Real-World Examples of LP/ILP/MIP
Unsupervised Learning of a Part-of-Speech Tagger

- based on Ravi & Knight 2009
### Part-of-speech tagging

**Input:** the lead paint is unsafe

**Output:** the/Det lead/N paint/N is/V unsafe/Adj

- **Partly supervised learning:**
  - You have a lot of text (without tags)
  - You have a dictionary giving possible tags for each word
What Should We Look At?

**correct tags**

Bill directed a cortege of autos through the dunes

Each unknown tag is *constrained* by its word and by the tags to its immediate left and right. But those tags are unknown too ...
What Should We Look At?

**correct tags**

Bill directed a cortege of autos through the dunes

Each unknown tag is **constrained** by its word and by the tags to its immediate left and right. But those tags are unknown too ...
What Should We Look At?

**correct tags**

Bill directed a cortege of autos through the dunes

Some possible tags for each word (maybe more)

Each unknown tag is **constrained** by its word and by the tags to its immediate left and right. But those tags are unknown too ...
Unsupervised Learning of a Part-of-Speech Tagger

- Given k tags (Noun, Verb, ...)
- Given a dictionary of m word types (aardvark, abacus, ...)
- Given some text: n word tokens (The aardvark jumps over...)
- Want to pick: n tags (Det Noun Verb Prep..)

- Encoding as variables?
- How to inject some knowledge about types and tokens?
- Constraints and objective?
  - Few tags allowed per word
  - Few 2-tag sequences allowed (e.g., “Det Det” is bad)
  - Tags may be correlated with one another, or with word endings
Minimum spanning tree ++

- based on Martins et al. 2009
Traveling Salesperson

- Version with subtour elimination constraints

- Version with auxiliary variables