Linear and Quadratic Programming (with CGAL)

Antonis Thomas, Algorithms Lab

November 2, 2016

Based on slides by Bernd Gärtner

Linear Programming (LP)

- **Problem:** Minimize a linear function in n variables subject to m linear (in)equality constraints!

Linear Programming

- **Problem:** Minimize a linear function in *n* variables subject to *m* linear (in)equality constraints!
- **Example** (*n*=2, *m*=5)**:**

$$\begin{array}{lrcl} \text{minimize} & -32y + 64 & & \\ \text{subject to} & x + y & \leq & 7 \\ & -x + 2y & \leq & 4 \\ & x & \geq & 0 \\ & y & \geq & 0 \\ & y & \leq & 4 \end{array}$$

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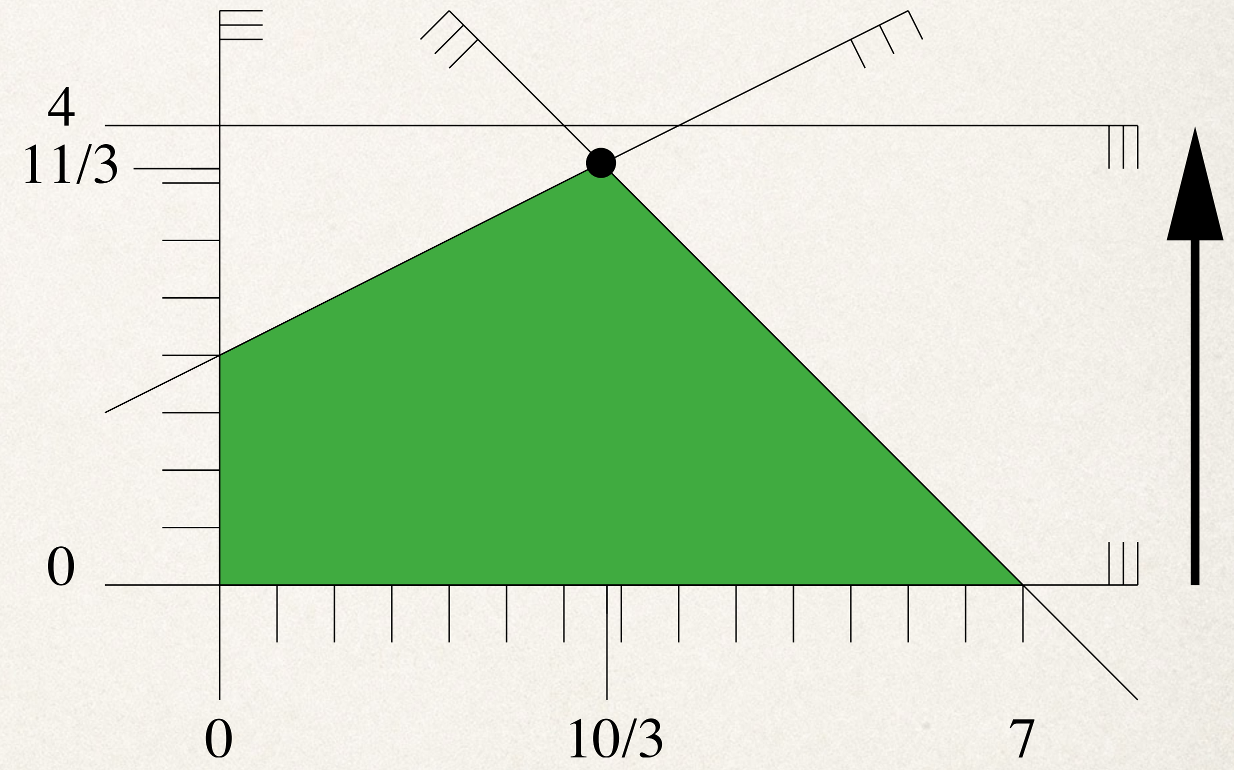

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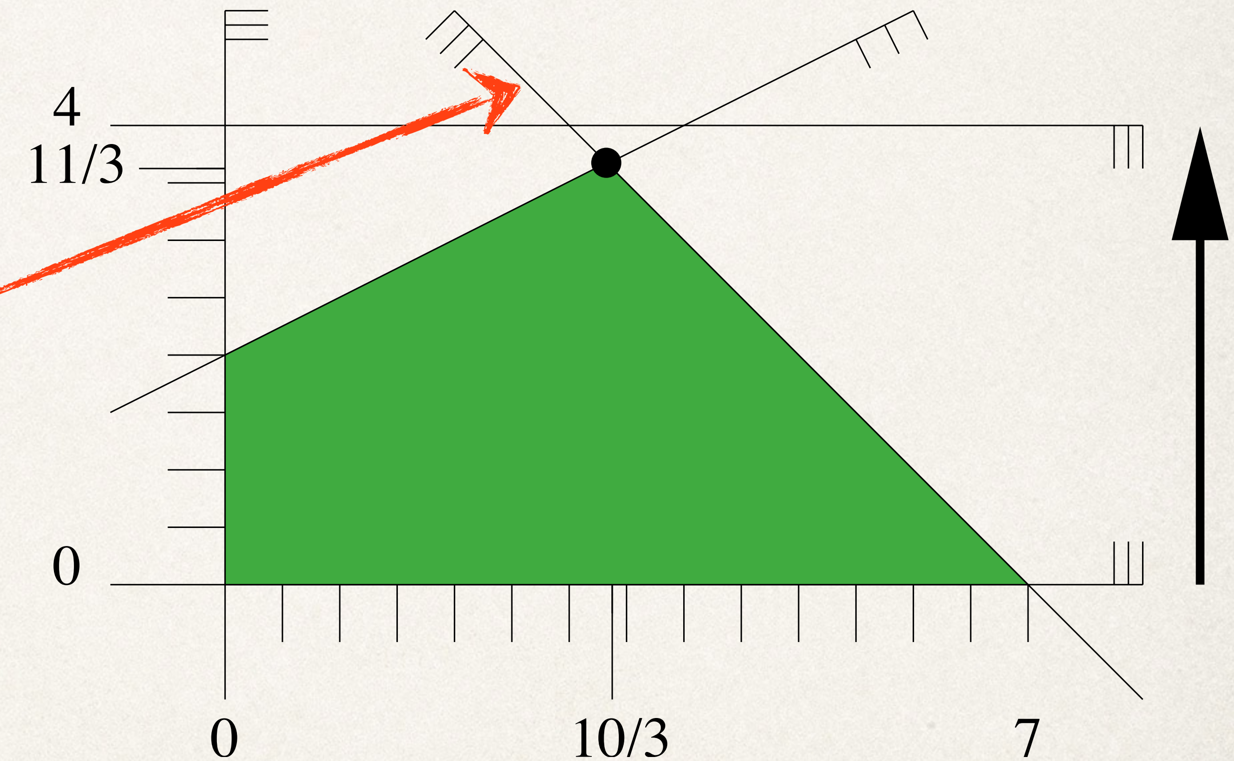

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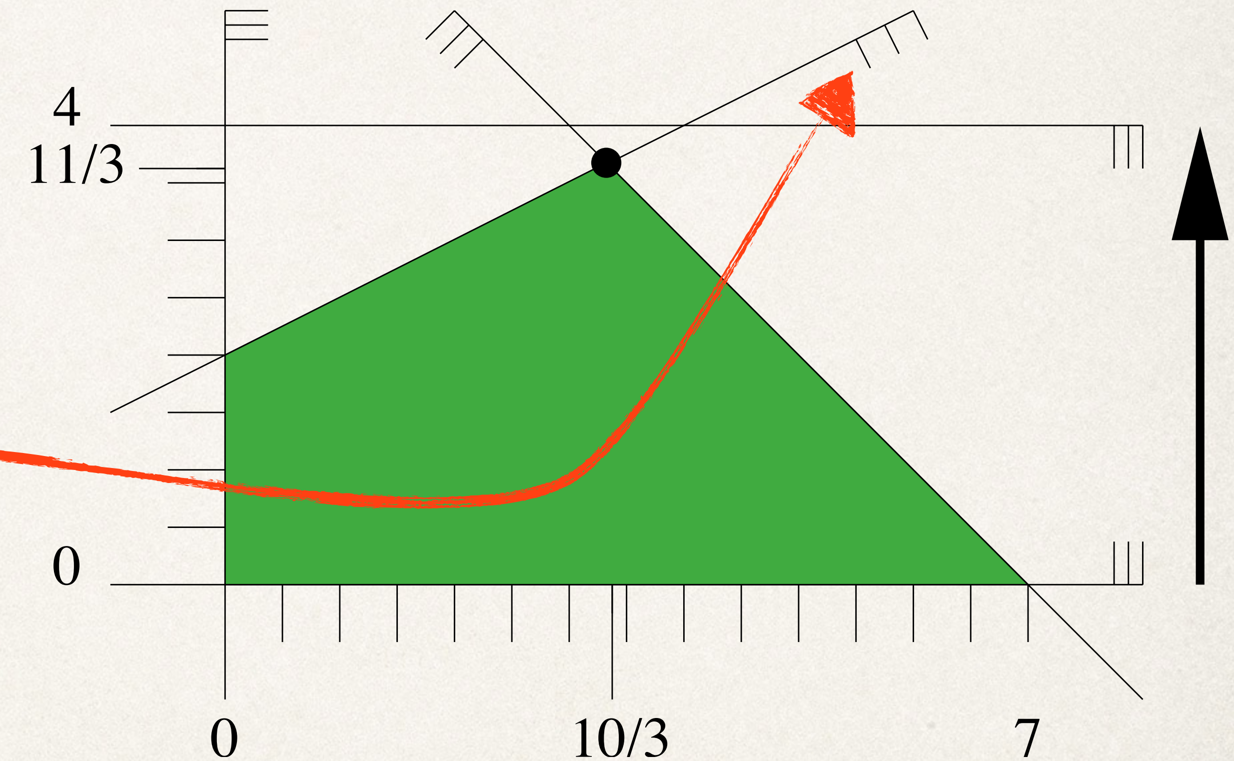

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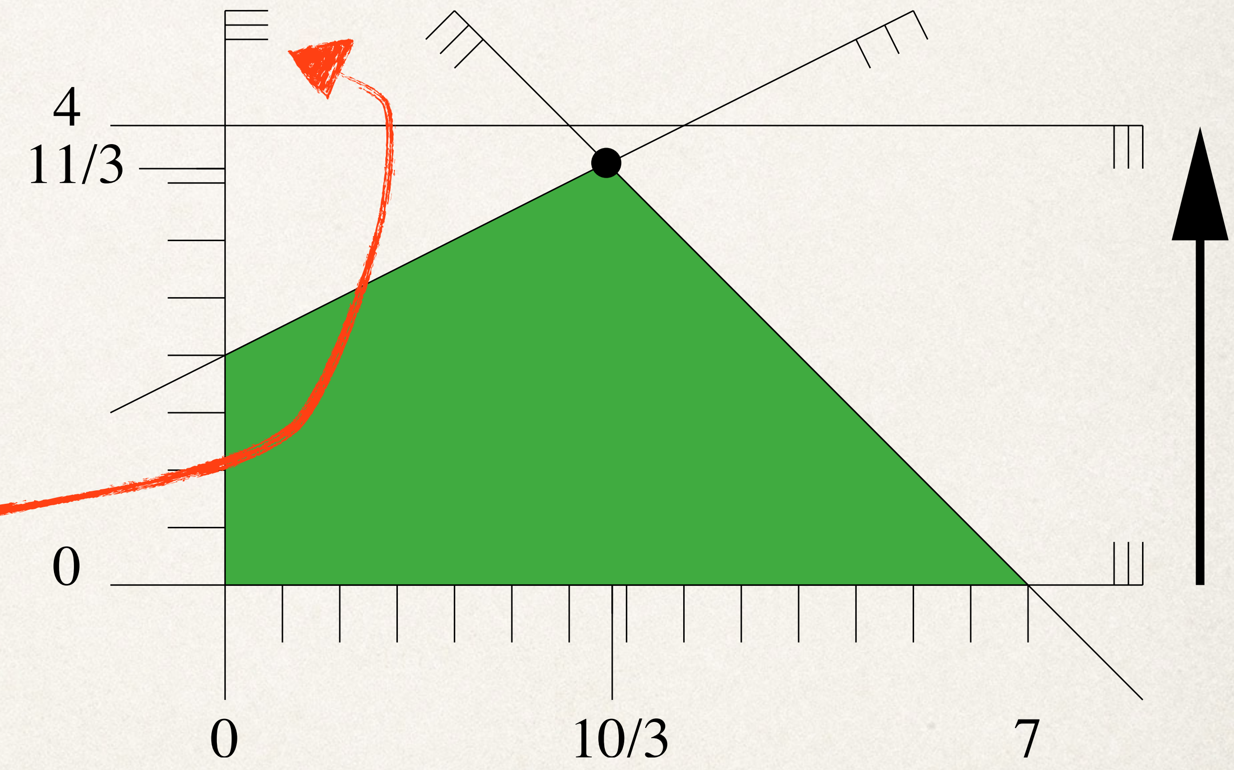

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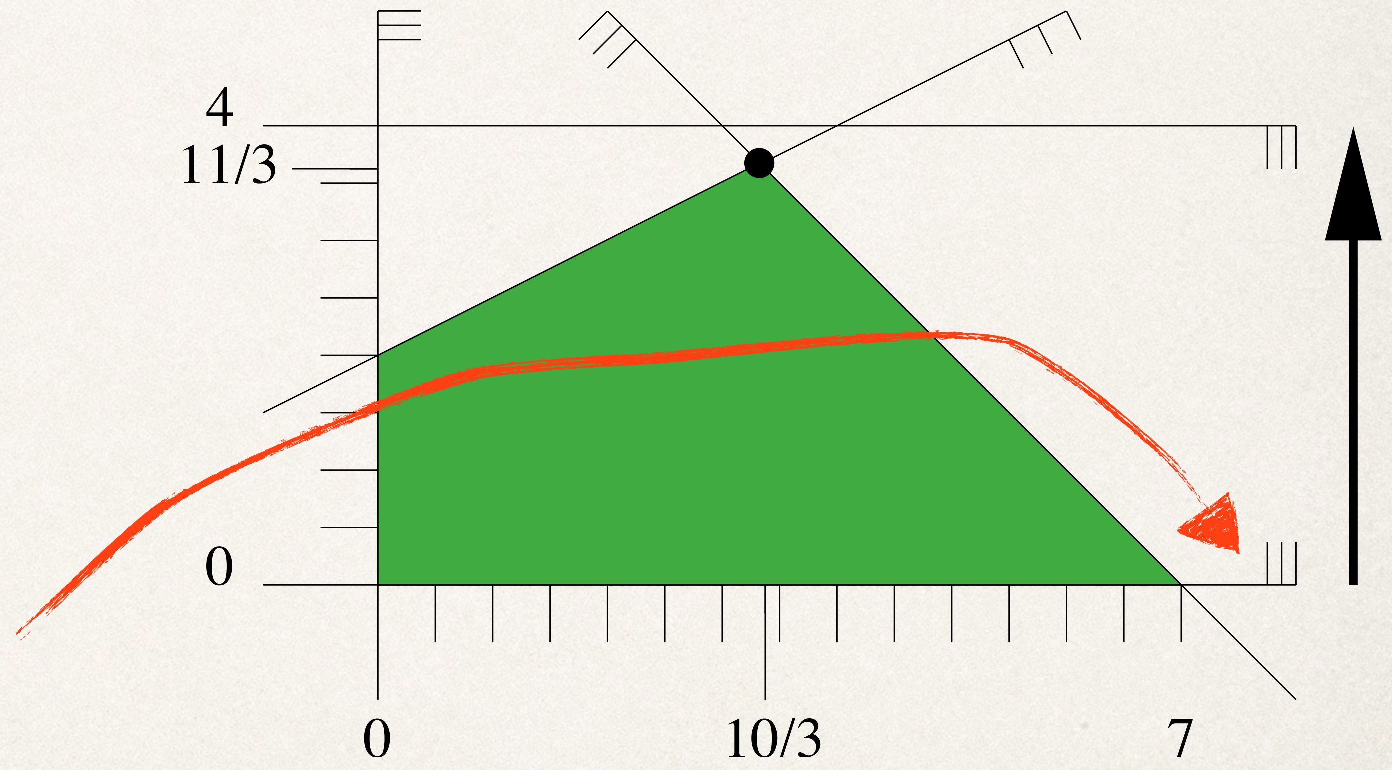

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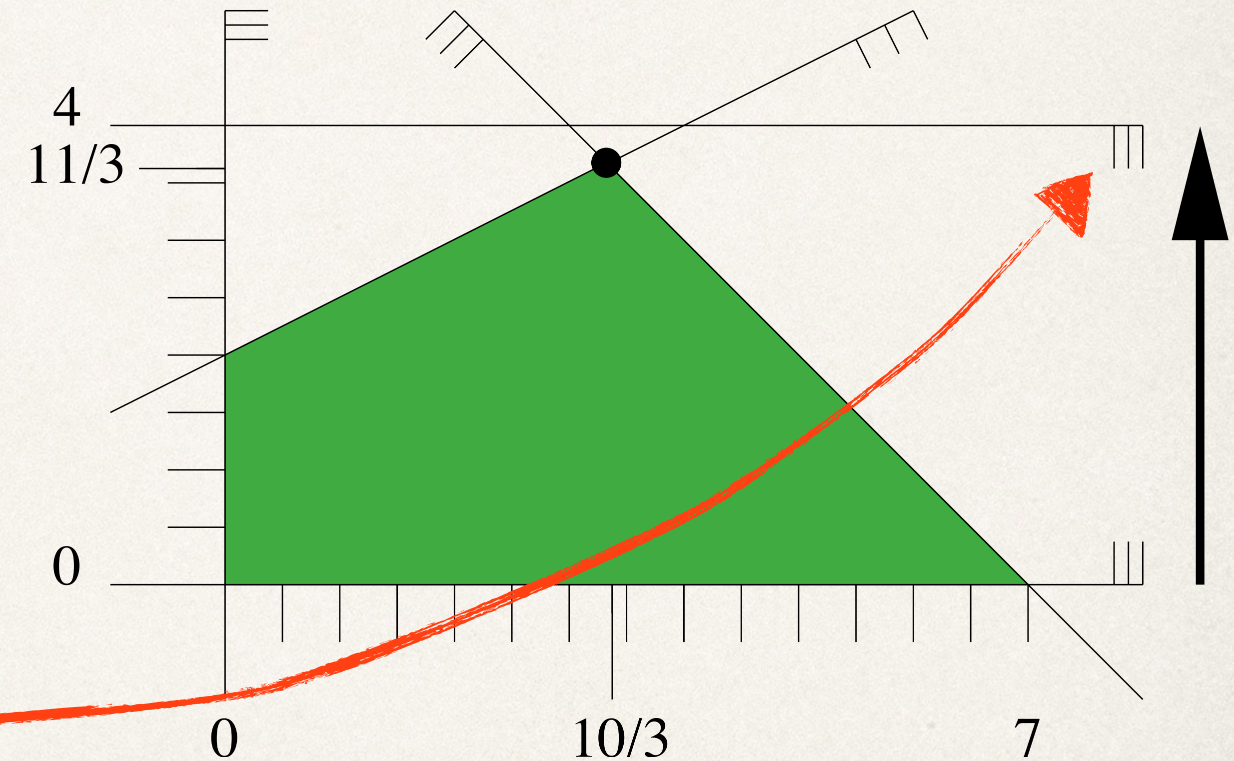

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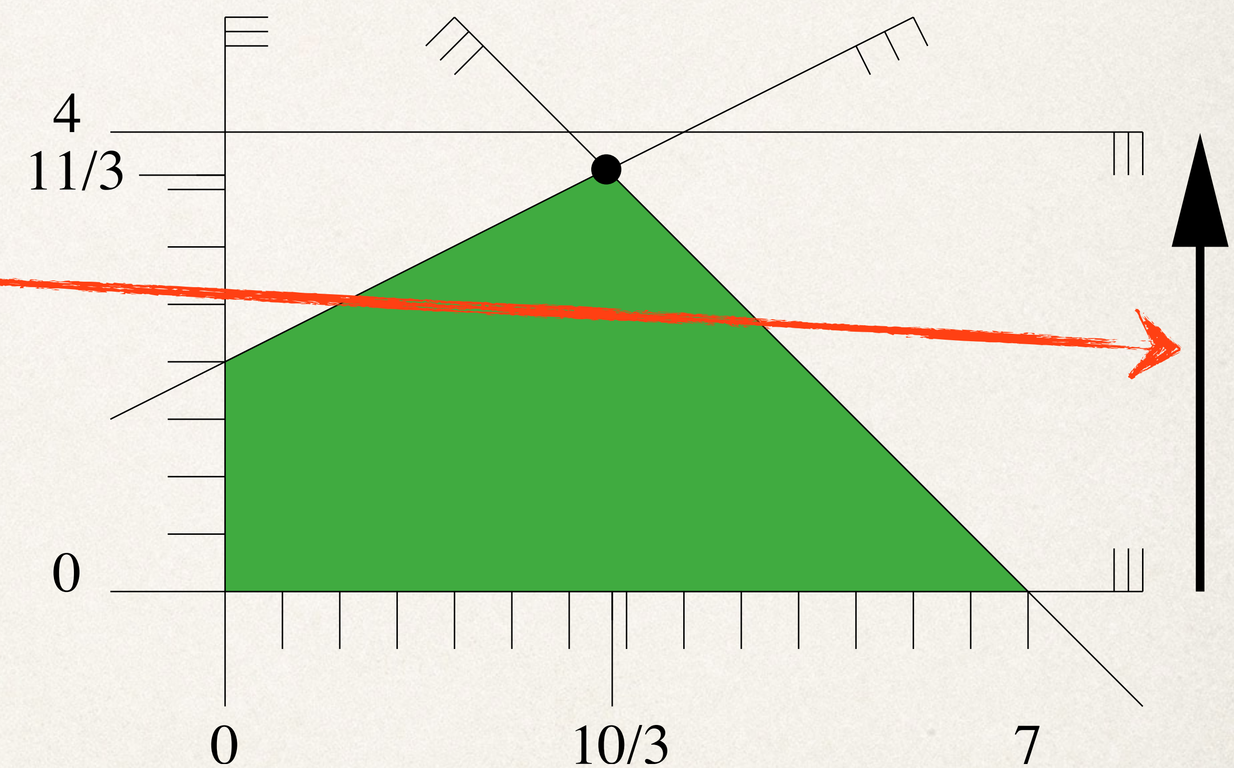

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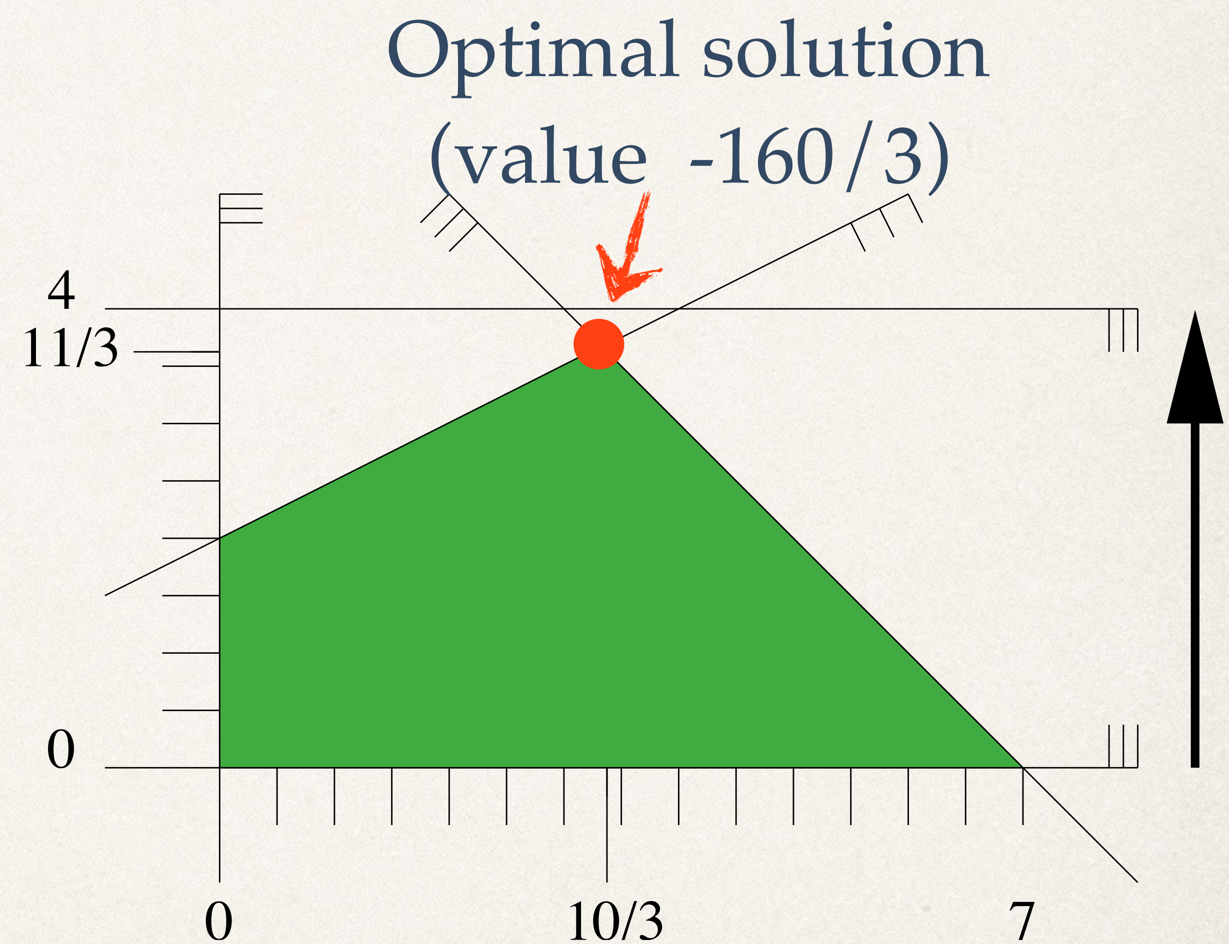
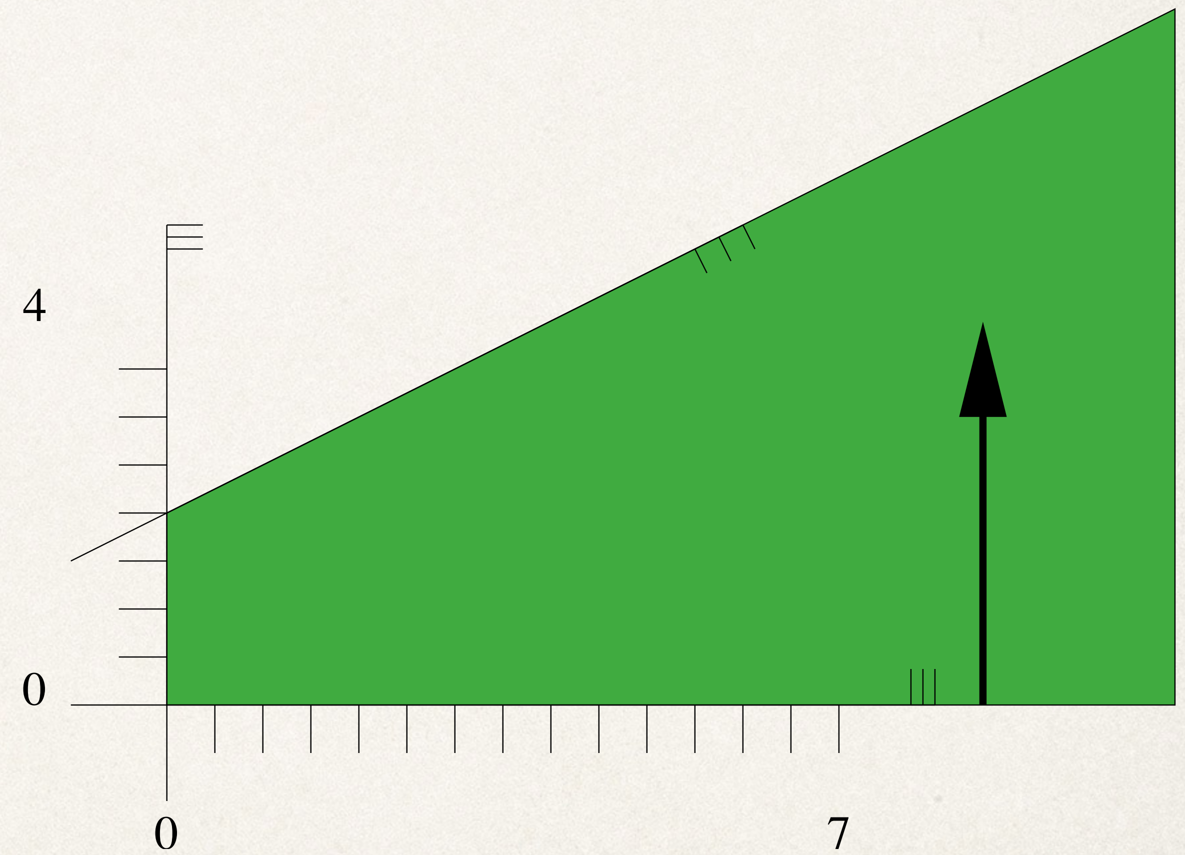


Linear Programming

- **Problem:** Minimize a linear function in *n* variables subject to *m* linear (in)equality constraints!

- **Unbounded linear programs:**

$$\begin{array}{llcl} \text{minimize} & -32y + 64 & & \\ \text{subject to} & \cancel{x + y} & \cancel{\leq} & \cancel{7} \\ & -x + 2y & \leq & 4 \\ & x & \geq & 0 \\ & y & \geq & 0 \\ & \cancel{y} & \cancel{\leq} & \cancel{4} \end{array}$$



Linear Programming

- **Problem:** Minimize a linear function in *n* variables subject to *m* linear (in)equality constraints!

- **Infeasible linear programs:**

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y \geq 4 & \cancel{y} & \cancel{\leq} & \cancel{4}
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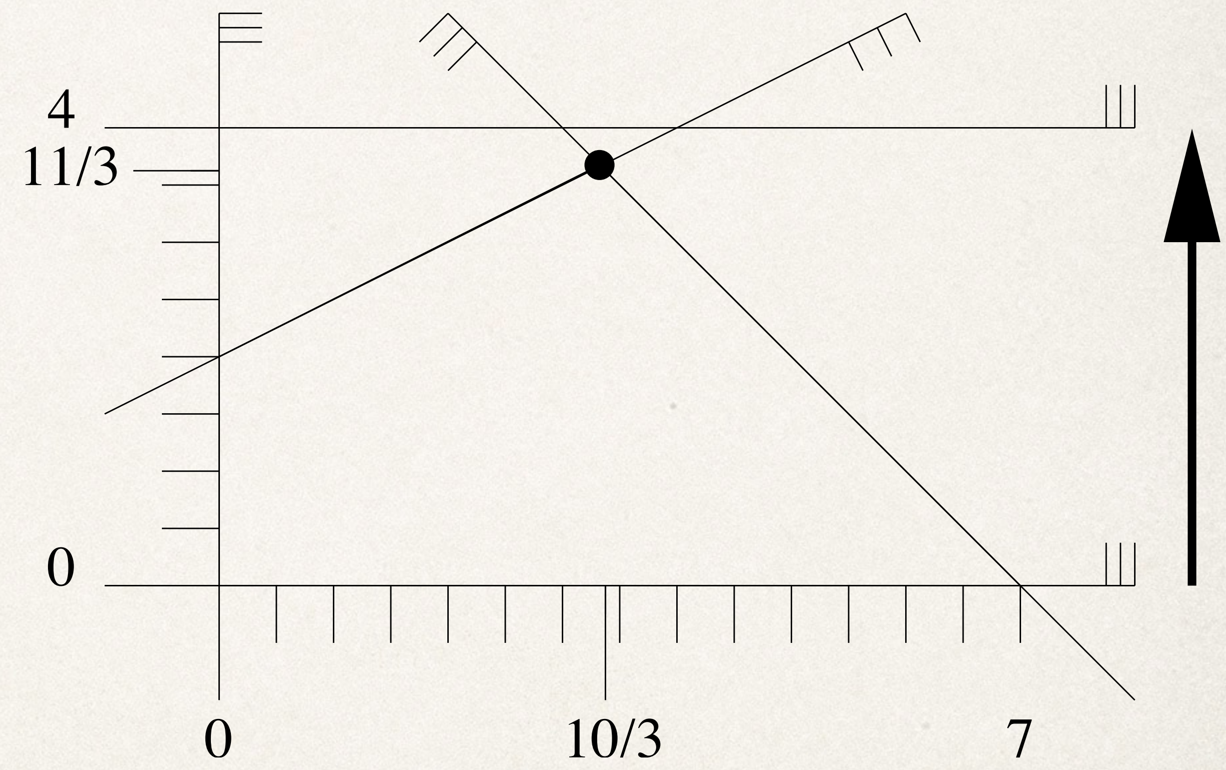
$$



Linear Programming ... in CGAL

- **General form of LP in CGAL:**

$$\begin{array}{ll} \text{minimize} & c^T x + c_0 \\ \text{subject to} & Ax \gtreqless b \\ & l \leq x \leq u \end{array}$$

$$(x, c, l, u \in \mathbb{R}^n, \quad A \in \mathbb{R}^{m \times n}, \quad b \in \mathbb{R}^m, \quad c_0 \in \mathbb{R})$$

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$$

≤, =, or ≥ (individually for each constraint)

variables

$$(x, c, l, u \in \mathbb{R}^n, \quad A \in \mathbb{R}^{m \times n}, \quad b \in \mathbb{R}^m, \quad c_0 \in \mathbb{R})$$

objective function

shift

lower and upper bounds

right-hand side

constraint matrix

Linear Programming ... in CGAL

$$
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$$

- **Preamble:** Choice of input type and exact internal number type

Gnu Multi-precision Library (GMP)

```
#include <iostream>
#include <cassert>
#include <CGAL/basic.h>
#include <CGAL/QP_models.h>
#include <CGAL/QP_functions.h>
#include <CGAL/Gmpz.h>

// choose exact integral type
typedef CGAL::Gmpz ET;




// program and solution types
typedef CGAL::Quadratic_program<int> Program;
typedef CGAL::Quadratic_program_solution<ET> Solution;
```

input type

exact internal type

for linear *and* quadratic programs

GMP used internally

Linear Programming ... in CGAL

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\end{array}
$$

- **Setup:** Enter the program data

```
int main() {
  // by default, we have a nonnegative LP with Ax <= b
  Program lp (CGAL::SMALLER, true, 0, false, 0);

  // now set the non-default entries
  const int X = 0;
  const int Y = 1;
  lp.set_a(X, 0,  1); lp.set_a(Y, 0, 1); lp.set_b(0, 7);  //  x + y  <= 7
  lp.set_a(X, 1, -1); lp.set_a(Y, 1, 2); lp.set_b(1, 4);  // -x + 2y <= 4
  lp.set_u(Y, true, 4);                                   //       y <= 4
  lp.set_c(Y, -32);                                       // -32y
  lp.set_c0(64);                                          // +64
```

$l =$ $(0,0,\ldots,0)$ $u = (\infty,\infty,\ldots,\infty)$

variable index (0,1,...)

constraint index (0,1,...)

last argument: value

Linear Programming ... in CGAL

- **Solve:** Call the linear programming solver and output solution

```
  // solve the program, using ET as the exact type
  Solution s = CGAL::solve_linear_program(lp, ET());
  assert (s.solves_linear_program(lp));

  // output solution
  std::cout << s;
  return 0;
}
```

independent verification

Linear Programming ... in CGAL

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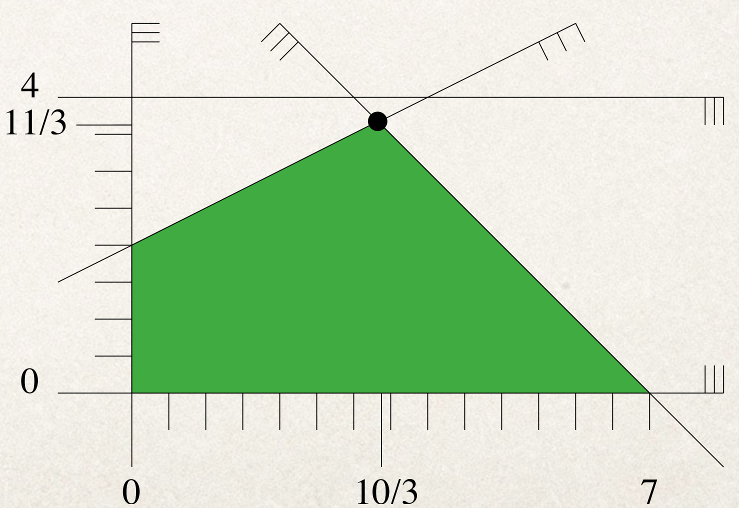
```

independent verification

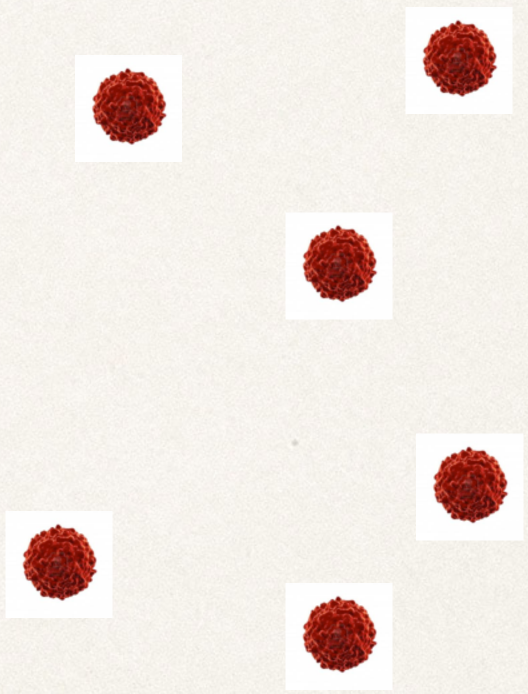
- **Output:**

```
status:            OPTIMAL
objective value: -160/3
variable values:
  0: 10/3
  1: 11/3
```



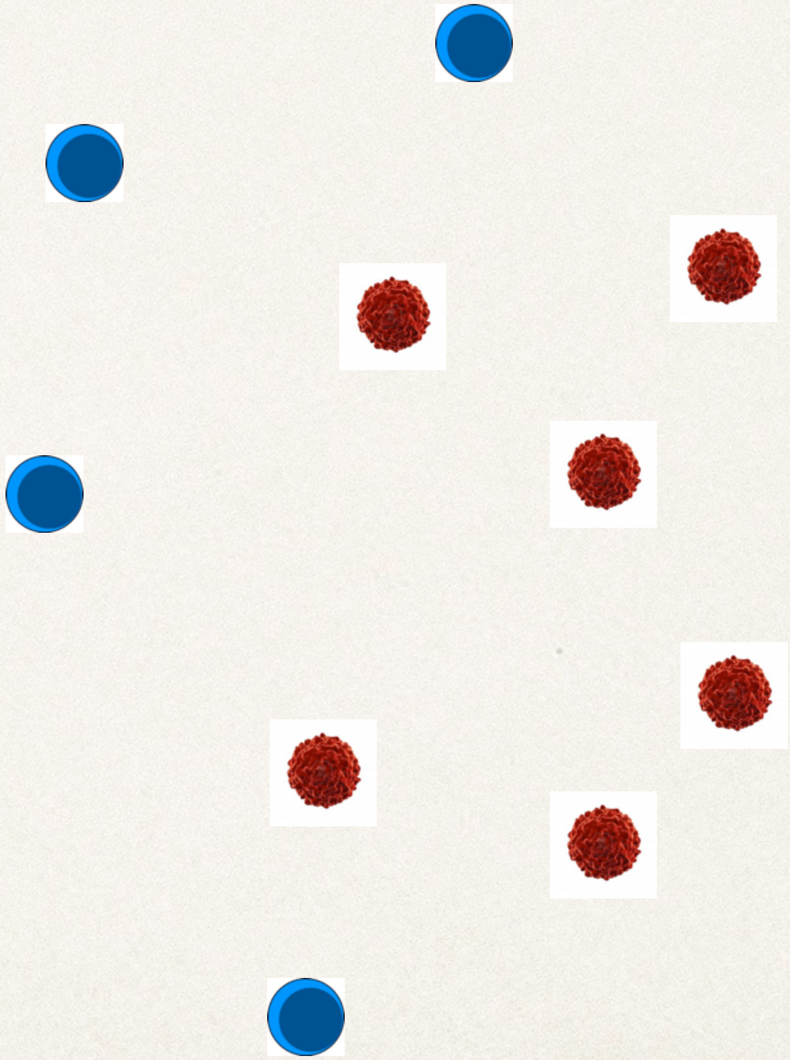
Linear Programming Application I: Cancer Therapy

- **Given:** locations of cancer cells (red)



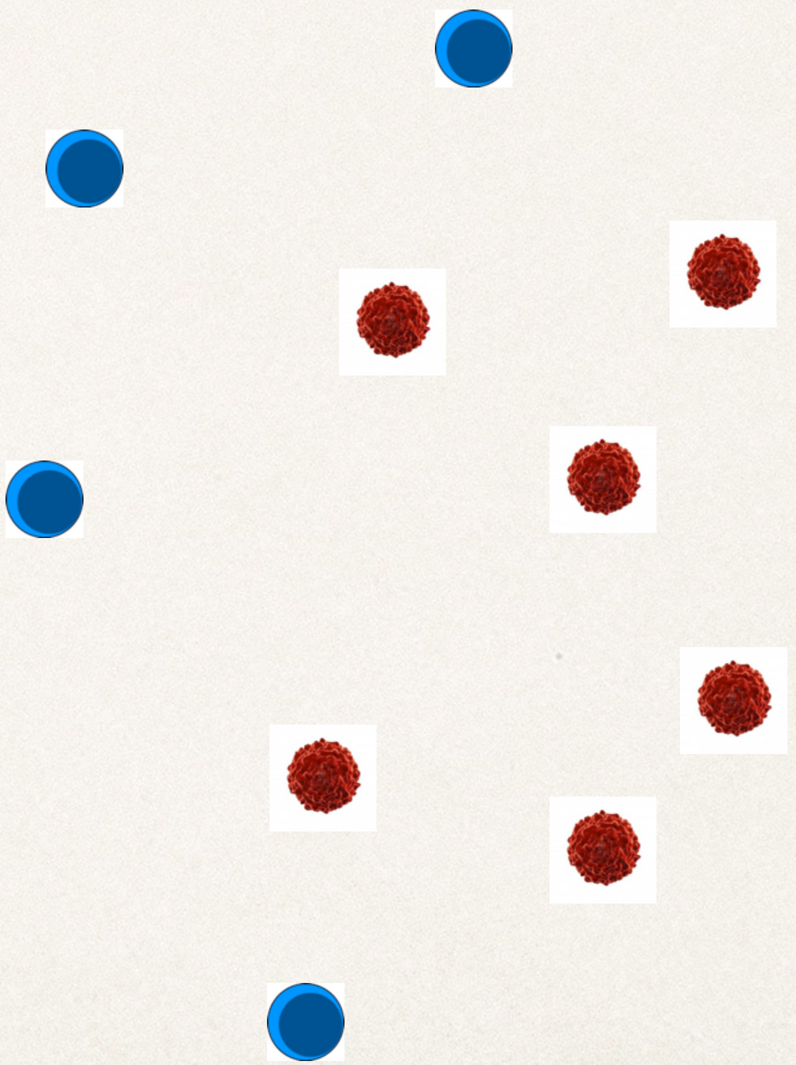
Linear Programming Application I: Cancer Therapy

- **Given:** locations of cancer cells (red) and healthy cells (blue)



Linear Programming Application I: Cancer Therapy

- **Given:** locations of cancer cells (red) and healthy cells (blue)
- **Wanted:** center and radius of exposure so that all cancer cells are killed and all healthy cells are unaffected.



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- **Given:** locations of cancer cells (red) and healthy cells (blue)
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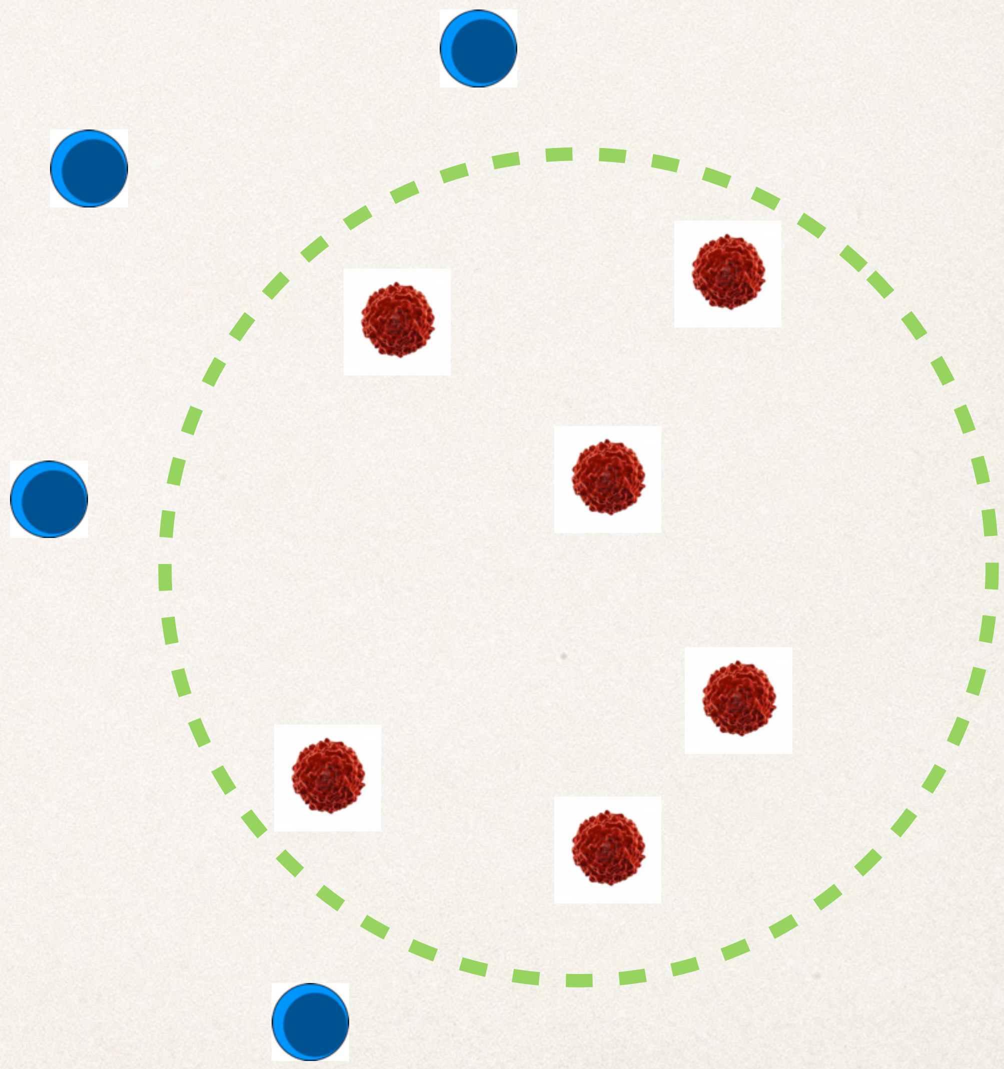
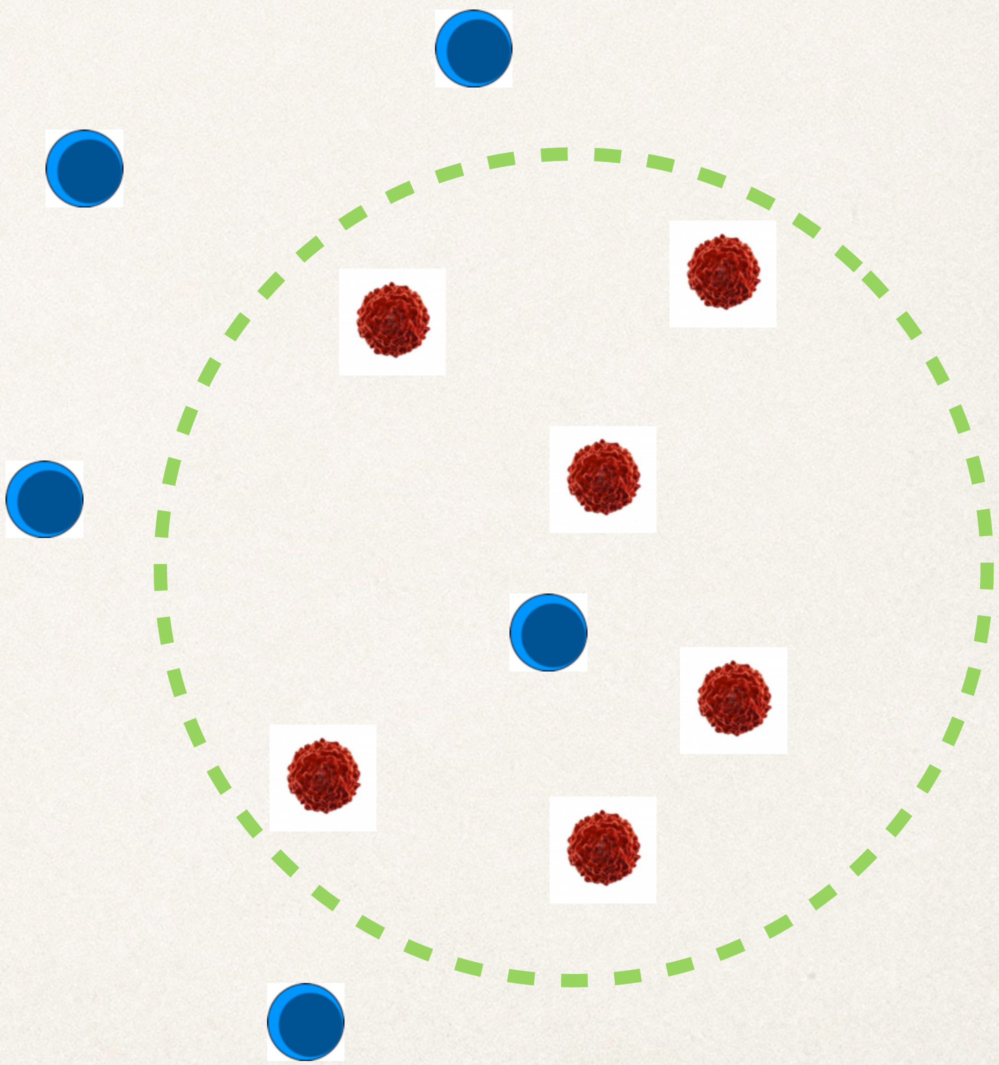
- This may be possible...



Linear Programming Application I: Cancer Therapy

- **Given:** locations of cancer cells (red) and healthy cells (blue)
- **Wanted:** center and radius of exposure so that all cancer cells are killed and all healthy cells are unaffected.
- This may be possible... or not.



Linear Programming Application I: Cancer Therapy

- **The geometric problem:** Given two finite sets R and B in the plane, does there exist a disk that contains R and is disjoint from B?

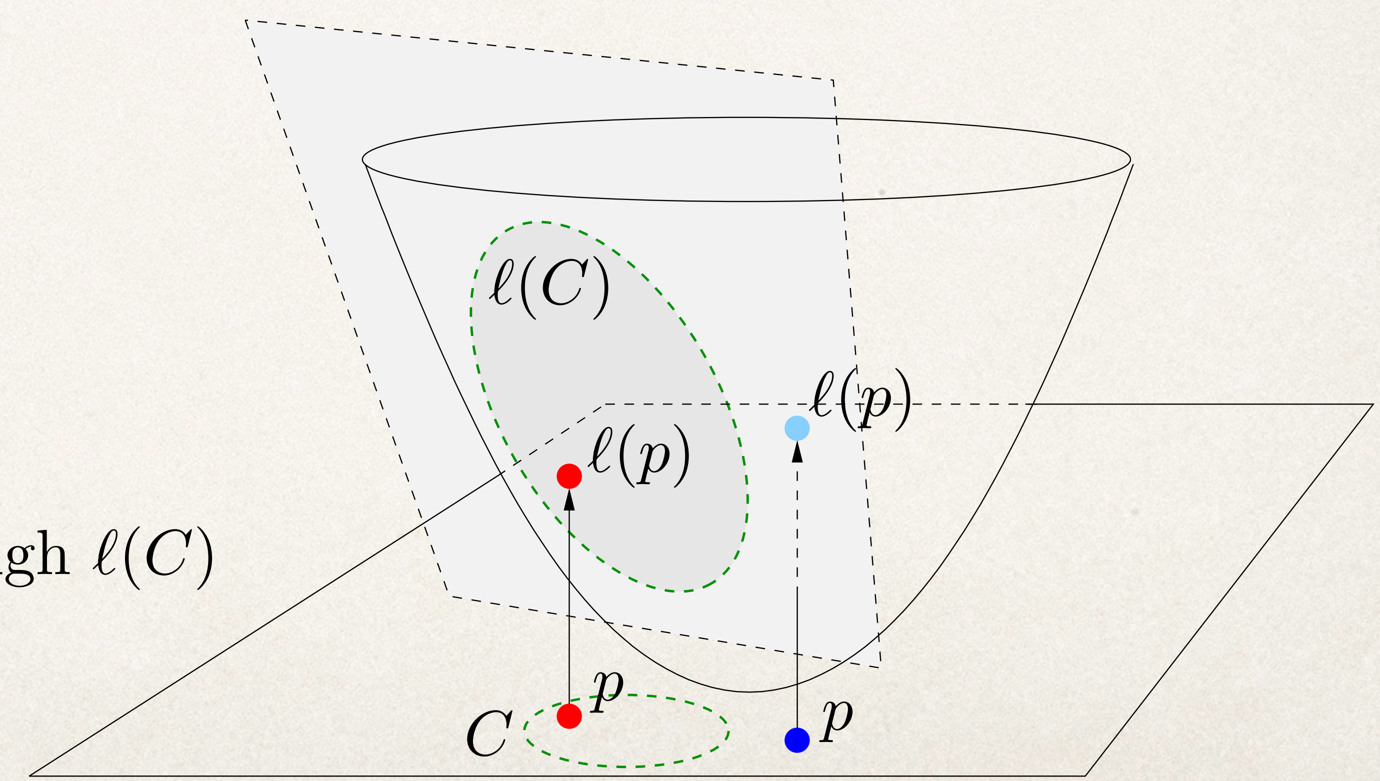
Linear Programming Application I: Cancer Therapy

- **The geometric problem:** Given two finite sets R and B in the plane, does there exist a disk that contains R and is disjoint from B?
- Apply *lifting map* $\ell : (x, y) \mapsto (x, y, x^2 + y^2)$ [Ref: Section 2.3]

$$p \left\{ \begin{array}{l} \text{inside} \\ \text{on} \\ \text{outside} \end{array} \right\} C$$

$$\Updownarrow$$

$$\ell(p) \left\{ \begin{array}{l} \text{below} \\ \text{on} \\ \text{above} \end{array} \right\} \text{the plane through } \ell(C)$$



Linear Programming Application I: Cancer Therapy

- **The geometric problem (lifted space):** Given the lifted sets R' and B' in space, is there a plane that has R' below/on it and B' above?

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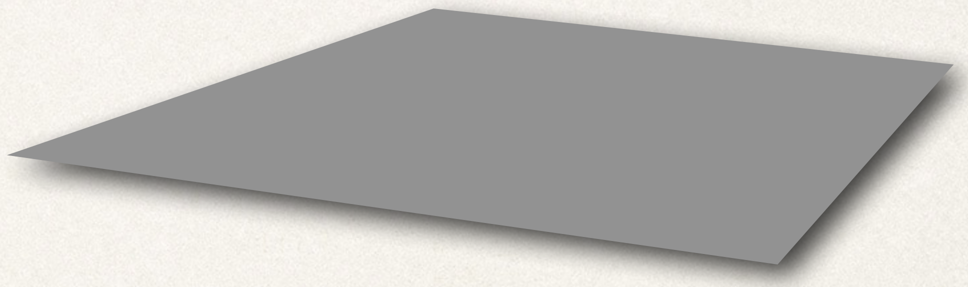
plane: $z = \alpha x + \beta y + \gamma$



Linear Programming Application I: Cancer Therapy

- **The geometric problem (lifted space):** Given the lifted sets R' and B' in space, is there a plane that has R' below/on it and B' above?
- This can be solved with linear programming!
- Find α, β, γ, δ ($\delta > 0$) such that...

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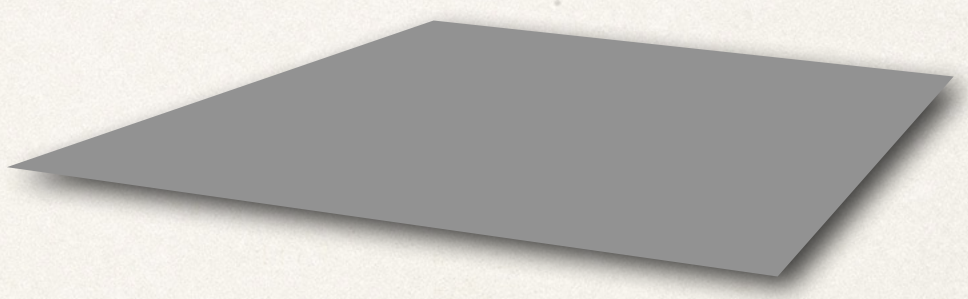

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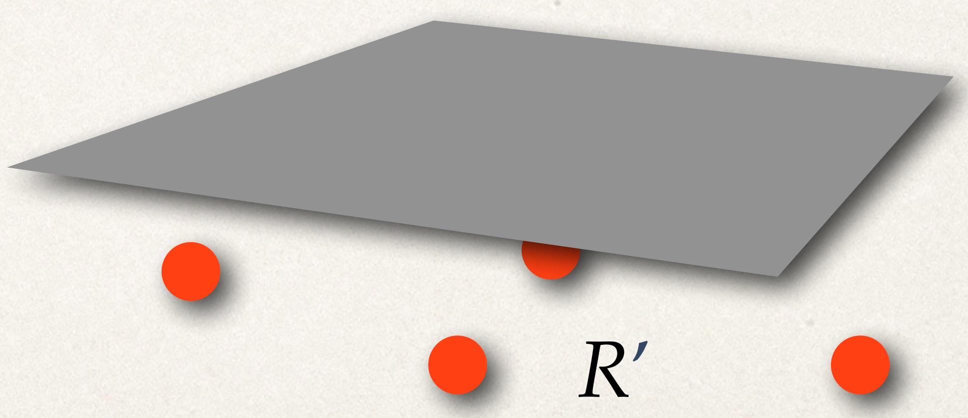

$$x^2 + y^2 \leq \alpha x + \beta y + \gamma, \quad (x, y) \in R$$

Linear Programming Application I: Cancer Therapy

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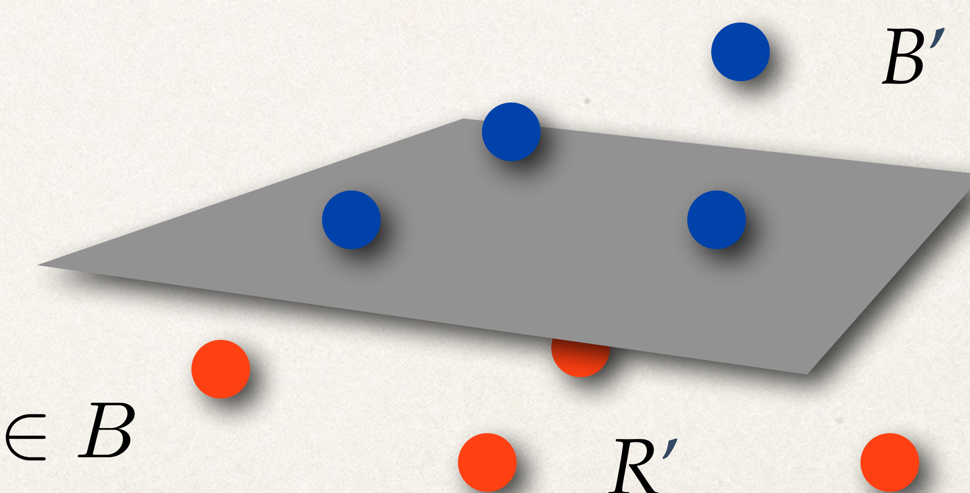

$$x^2 + y^2 \geq \alpha x + \beta y + \gamma + \delta, \quad (x, y) \in B$$

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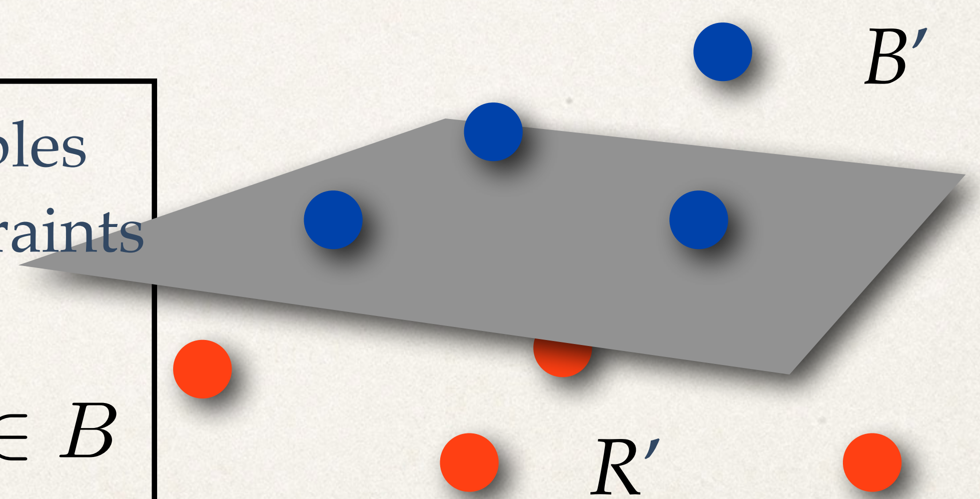

maximize δ

4 variables

|B|+|R| constraints

subject to

$$x^2 + y^2 \geq \alpha x + \beta y + \gamma + \delta, \quad (x, y) \in B$$

$$x^2 + y^2 \leq \alpha x + \beta y + \gamma, \quad (x, y) \in R$$

Linear Programming Application I: Cancer Therapy

- **Fact:** Exposure is possible if and only if the following linear program has positive value.

$$
\boxed{
\begin{array}{l}
\text{maximize } \delta \\[1em]
\text{subject to} \\[1em]
\quad x^2 + y^2 \geq \alpha x + \beta y + \gamma + \delta, \quad (x,y) \in B \\[0.5em]
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}
$$

Linear Programming Application I: Cancer Therapy

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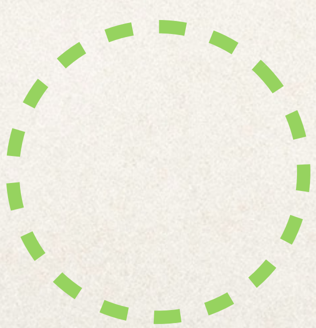
- **Reconstructing the exposure from an optimal solution** (α, β, γ, δ):



$$= \{(x,y) : x^2 + y^2 = \alpha x + \beta y + \gamma\}$$

Linear Programming Application I: Cancer Therapy

- **Fact:** Exposure is possible if and only if the following linear program has positive value.

$$\boxed{\begin{array}{l} \text{maximize } \delta \\ \text{subject to} \\ \quad x^2 + y^2 \geq \alpha x + \beta y + \gamma + \delta, \quad (x, y) \in B \\ \quad x^2 + y^2 \leq \alpha x + \beta y + \gamma, \quad (x, y) \in R \end{array}}$$

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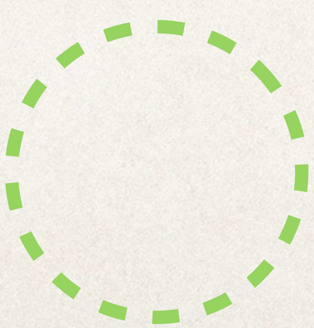


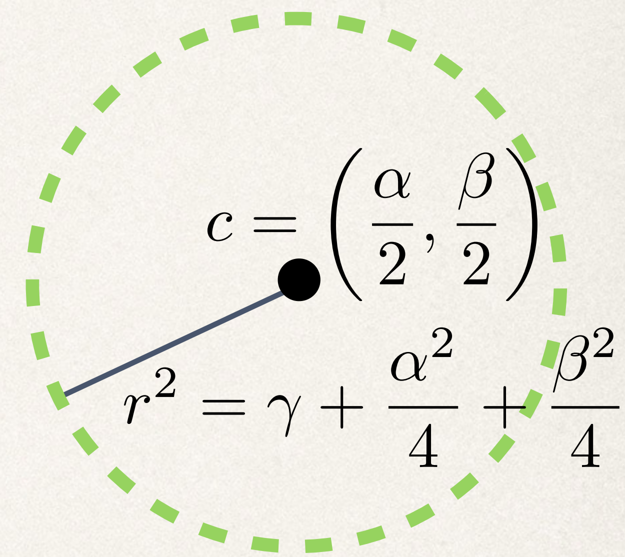
$$= \{(x, y) : x^2 + y^2 = \alpha x + \beta y + \gamma\}$$

$$= \{(x, y) : (x - \frac{\alpha}{2})^2 + (y - \frac{\beta}{2})^2 = \gamma + \frac{\alpha^2}{4} + \frac{\beta^2}{4}\}$$

Linear Programming Application I: Cancer Therapy

- **Fact:** Exposure is possible if and only if the following linear program has positive value.

$$\boxed{\begin{aligned}&\text{maximize } \delta\\ &\text{subject to}\\ &\quad x^2+y^2 \geq \alpha x+\beta y+\gamma+\delta, \quad (x,y)\in B\\ &\quad x^2+y^2 \leq \alpha x+\beta y+\gamma, \quad (x,y)\in R\end{aligned}}$$



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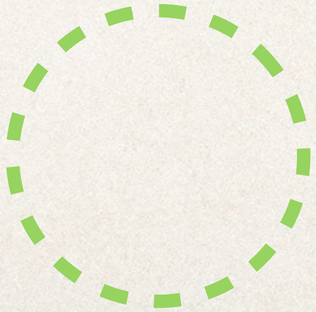

$$= \{(x,y) : x^2+y^2 = \alpha x+\beta y+\gamma\}$$

$$= \{(x,y) : (x-\frac{\alpha}{2})^2+(y-\frac{\beta}{2})^2 = \gamma+\frac{\alpha^2}{4}+\frac{\beta^2}{4}\}$$

Linear Programming Application I: Cancer Therapy

- **Implementation in CGAL:**

$$\boxed{\begin{array}{llcll} \text{minimize} & -\delta & & & \\ \text{subject to} & x^2+y^2 & \geq & \alpha x+\beta y+\gamma+\delta, & (x,y)\in B \\ & x^2+y^2 & \leq & \alpha x+\beta y+\gamma, & (x,y)\in R \\ & \delta & \leq & 1 & \end{array}}$$

Avoids unbounded program

maximize $c^T x \rightarrow$ minimize $-c^T x$ and negate resulting value

Linear Programming Application I: Cancer Therapy

- **Implementation in CGAL: Setup and Solve** (Preamble as before)

```
int main() {
  // by default, we have an LP with Ax <= b and no bounds for
  // the four variables alpha, beta, gamma, delta
  Program lp (CGAL::SMALLER, false, 0, false, 0);
  const int alpha = 0;
  const int beta  = 1;
  const int gamma = 2;
  const int delta = 3;

  // number of red and blue points
  int m; std::cin >> m;
  int n; std::cin >> n;

  // read the red points (cancer cells)
  for (int i=0; i<m; ++i) {
    int x; std::cin >> x;
    int y; std::cin >> y;
    // set up <= constraint for point inside/on circle:
    //   -alpha x - beta y - gamma <= -x^2 - y^2
    lp.set_a (alpha, i, -x);
    lp.set_a (beta,  i, -y);
    lp.set_a (gamma, i, -1);
    lp.set_b (       i, -x*x - y*y);
  }
```

```
  // read the blue points (healthy cells)
  for (int j=0; j<n; ++j) {
    int x; std::cin >> x;
    int y; std::cin >> y;
    // set up <= constraint for point outside circle:
    //   alpha x + beta y + gamma + delta <= x^2 + y^2
    lp.set_a (alpha, m+j, x);
    lp.set_a (beta,  m+j, y);
    lp.set_a (gamma, m+j, 1);
    lp.set_a (delta, m+j, 1);
    lp.set_b (       m+j, x*x + y*y);
  }

  // objective function: -delta (the solver minimizes)
  lp.set_c(delta, -1);

  // enforce a bounded problem:
  lp.set_u (delta, true, 1);

  // solve the program, using ET as the exact type
  Solution s = CGAL::solve_linear_program(lp, ET());
  assert (s.solves_linear_program(lp));
```

Linear Programming Application I: Cancer Therapy

- **Implementation in CGAL: Output**

negate resulting value!

```
  // output exposure center and radius, if they exist
  if (s.is_optimal() && (s.objective_value() < 0)) {
    // *opt := alpha, *(opt+1) := beta, *(opt+2) := gamma
    CGAL::Quadratic_program_solution<ET>::Variable_value_iterator
      opt = s.variable_values_begin();
    CGAL::Quotient<ET> alpha = *opt;
    CGAL::Quotient<ET> beta = *(opt+1);
    CGAL::Quotient<ET> gamma = *(opt+2);
    std::cout << "There is a valid exposure:\n";
    std::cout << " Center = ("         // (alpha/2, beta/2)
         << alpha/2 << ", " <<  beta/2
         << ")\n";
    std::cout << " Squared Radius = " // gamma + alpha^2/4 + beta^2/4
         << gamma + alpha*alpha/4 + beta*beta/4 << "\n";
  } else
    std::cout << "There is no valid exposure.";
  std::cout << "\n";
  return 0;
}
```

Linear Programming Application I: Cancer Therapy

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         << gamma + alpha*alpha/4 + beta*beta/4 << "\n";
  } else
    std::cout << "There is no valid exposure.";
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  return 0;
}
```
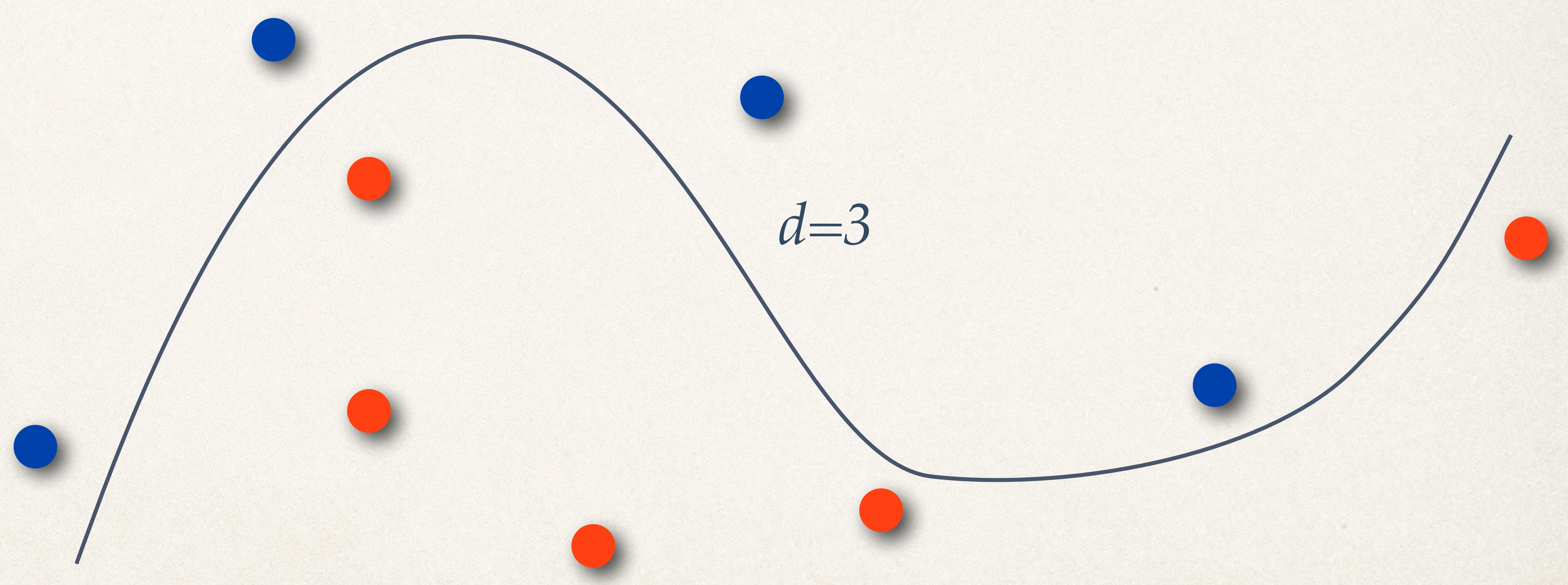

"Pointer" to first variable of optimal solution

The quotient **`*(opt+i)`** is the value of the variable x_i in the optimal solution

Linear Programming Beyond Cancer Therapy

- Given a set of R of red and a set B of blue points, can they be separated by the zero set of a polynomial of degree *d*?



Linear Programming Beyond Cancer Therapy

- Given a set of R of red and a set B of blue points, can they be separated by the zero set of a polynomial of degree *d*?
- Polynomial of degree 3:

$$ax^3 + bx^2y + cxy^2 + dy^3 + ex^2 + fxy + gy^2 + hx + iy + j$$

Linear Programming Beyond Cancer Therapy

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- Linear programming formulation: find *a,b,c,d,e,f,g,h,i,j* such that

$$ax^3 + bx^2y + cxy^2 + dy^3 + ex^2 + fxy + gy^2 + hx + iy + j \leq 0, \quad (x, y) \in B$$
$$ax^3 + bx^2y + cxy^2 + dy^3 + ex^2 + fxy + gy^2 + hx + iy + j \geq 0, \quad (x, y) \in R$$

Linear Programming Further Applications

- Linear programming relaxations for hard combinatorial problems

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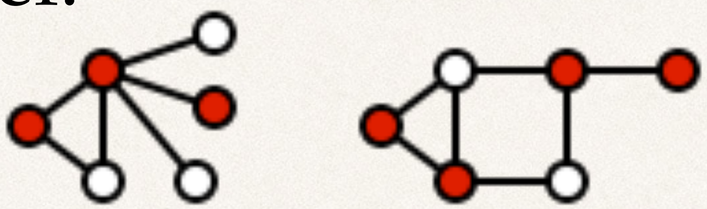
- **Vertex Cover:** Given a graph G=(V,E), find a smallest subset of vertices (a vertex cover) such that every edge is incident to one vertex of the cover.



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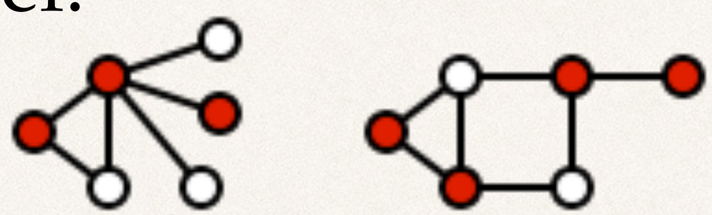

- Formulation as "LP": x_i indicates whether vertex i is in the cover (0: not in the cover, 1: in the cover):

$$\begin{array}{llcl} \text{minimize} & \sum_{i=1}^{n} x_i & & \\ \text{subject to} & x_i + x_j \geq 1 & & \forall \{i,j\} \in E \\ & 0 \leq x_i \leq 1 & & \forall i \in V \end{array}$$

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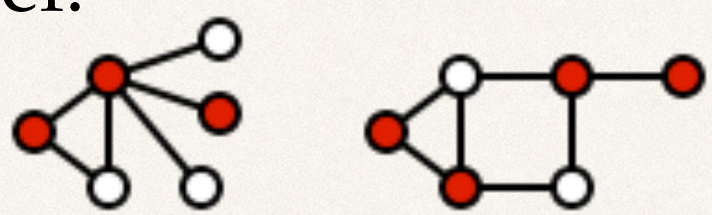

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 & 0 \leq x_i \leq 1 & & & \forall i \in V \\
 & x_i \in \{0,1\} & & & \forall i \in V \quad \longleftarrow \text{not an LP!}
\end{array}
$$

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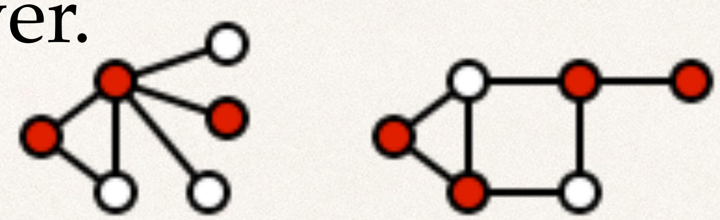

- Let $x^*_1, x^*_2, \ldots, x^*_n$ be an optimal solution of the *LP relaxation*

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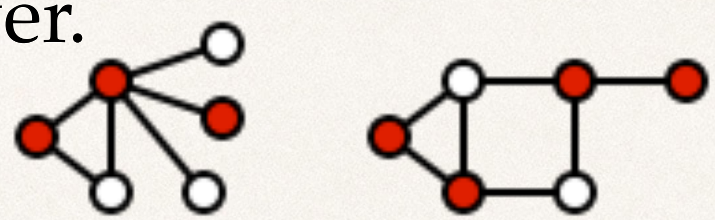

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\end{array}
$$

- **Theorem:** $C = \{i : x^*_i \geq 1/2\}$ is a vertex cover of size at most 2 opt.

[Ref]

Linear vs. Integer Programming

- Often, applications lead to linear programs with the additional requirement of *integral solutions* (e.g. vertex cover)

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- Such programs are called *integer linear programs* (ILP) and are in general much harder to solve than linear programs (NP-hard)

Linear vs. Integer Programming

- Often, applications lead to linear programs with the additional requirement of *integral solutions* (e.g. vertex cover)
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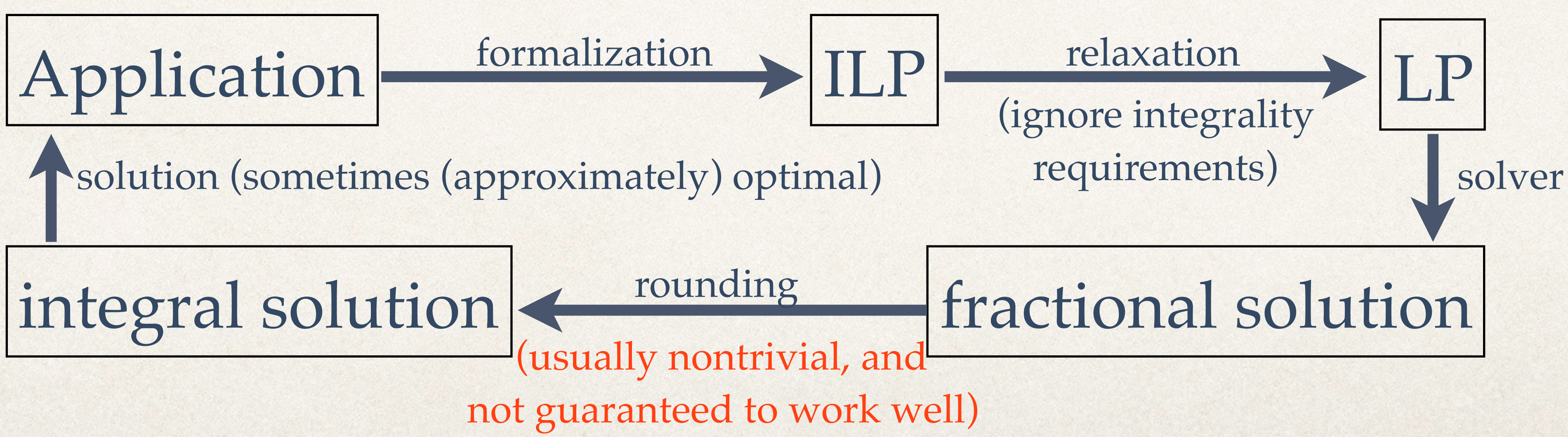
- Typical approach (e.g. vertex cover):



Quadratic Programming (QP)

- **Problem:** Minimize a convex quadratic function in n variables subject to m linear (in)equality constraints!

Quadratic Programming

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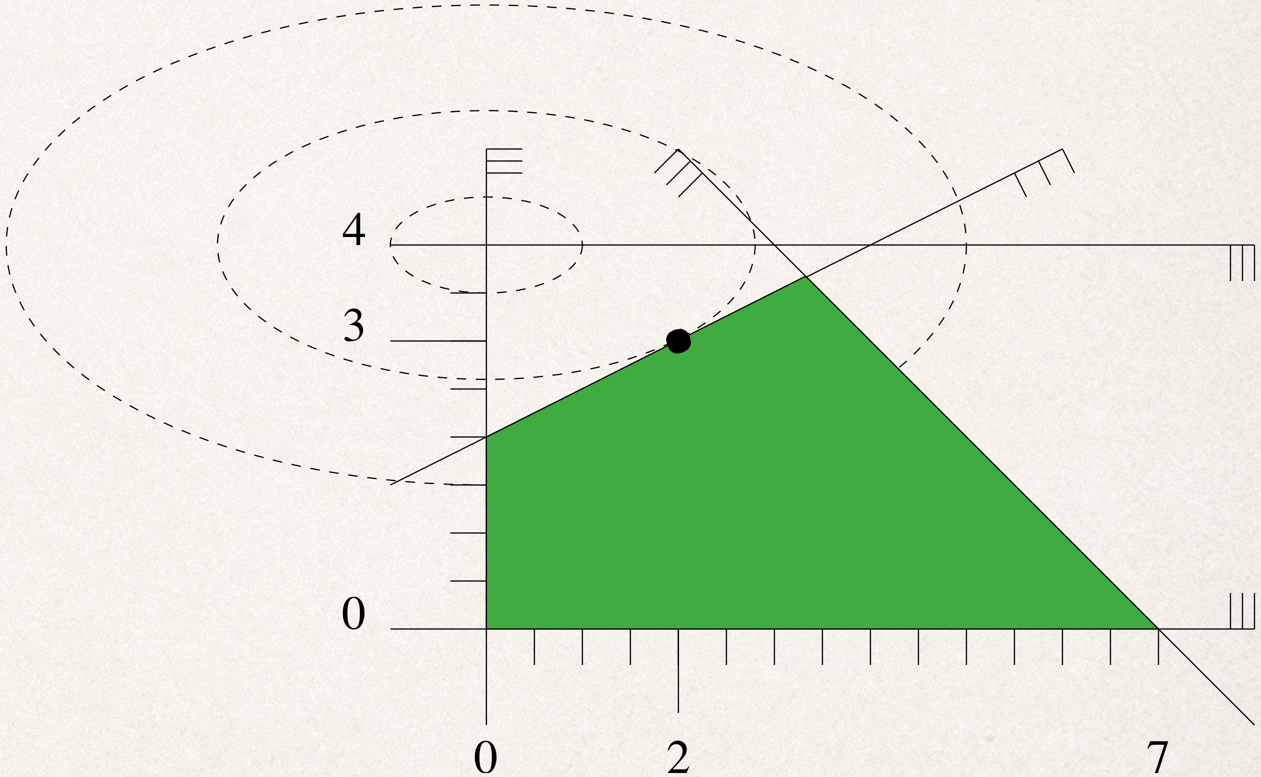
- **Example** (n=2, m=5):

$$\begin{array}{lrcr} \text{minimize} & x^2 + 4y^2 - 32y + 64 & & \\ \text{subject to} & x + y & \leq & 7 \\ & -x + 2y & \leq & 4 \\ & x & \geq & 0 \\ & y & \geq & 0 \\ & y & \leq & 4 \end{array}$$



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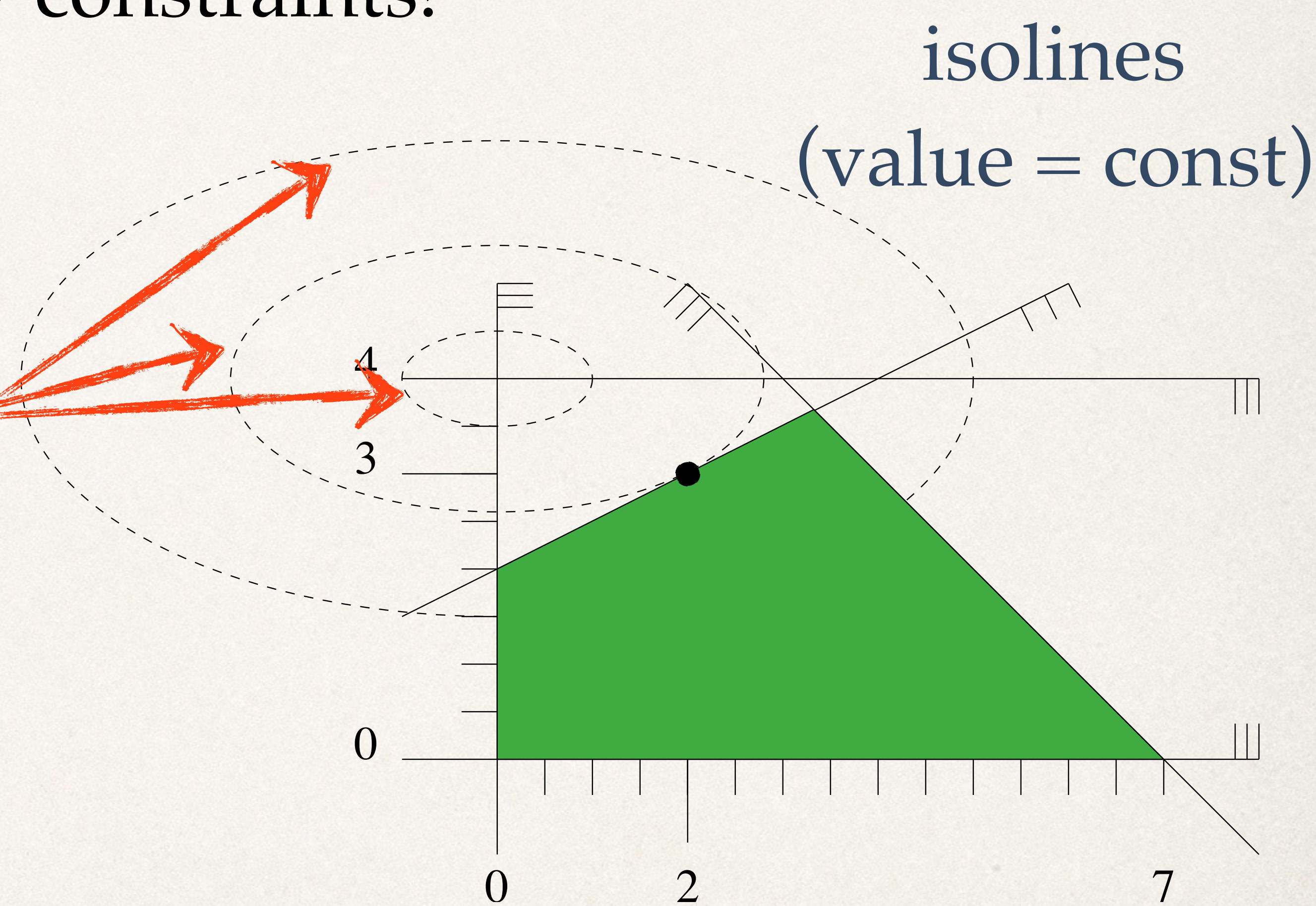

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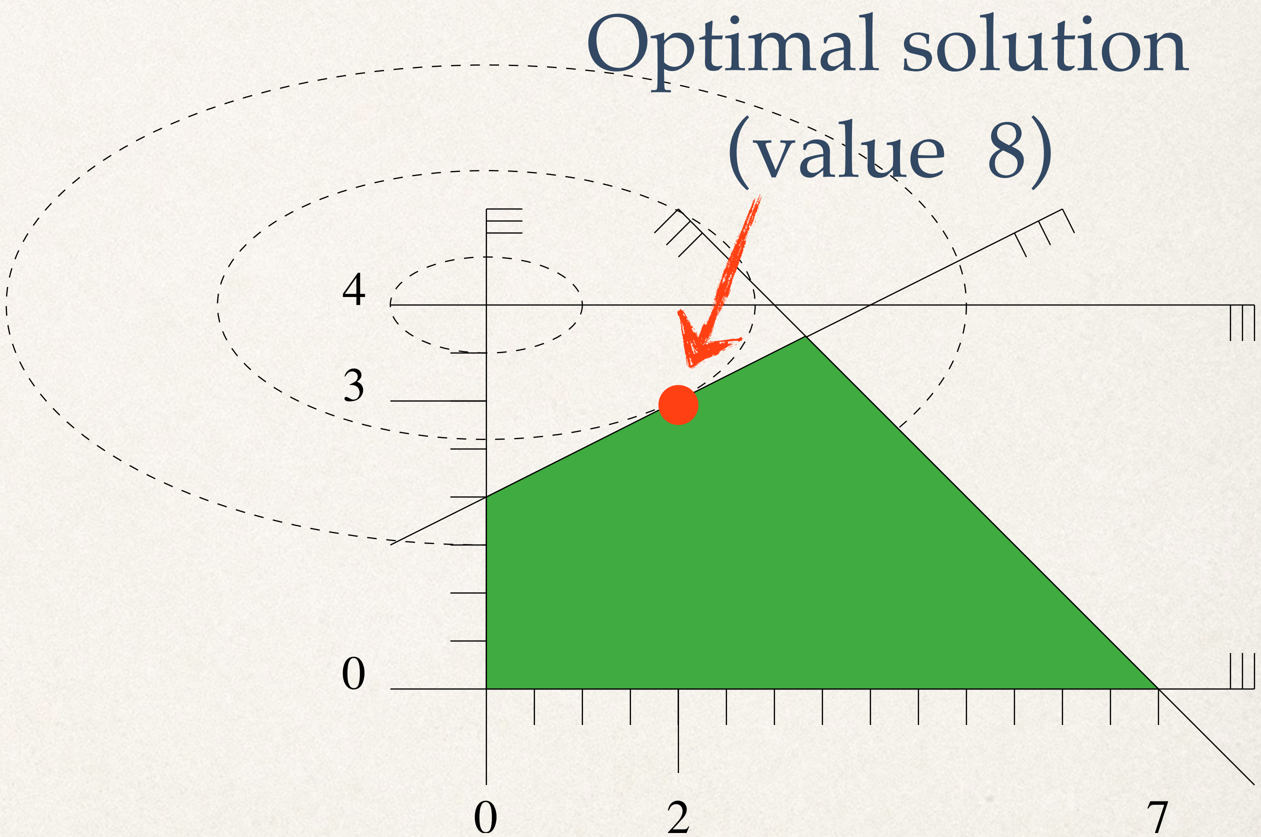

Quadratic Programming ... in CGAL

- **General form of QP in CGAL:**

$$
\begin{array}{ll}
\text{minimize} & x^T D x + c^T x + c_0 \\
\text{subject to} & A x \overset{\geq}{\underset{\leq}{=}} b \\
 & l \leq x \leq u
\end{array}
$$

$(D \in \mathbb{R}^{n \times n}$ symmetric positive semidefinite$)$

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- **Relax:** In the applications, we know from theory that *D* is "good"

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- **Example:**

$$\begin{array}{llcr} \text{minimize} & x^2 + 4y^2 - 32y + 64 & & \\ \text{subject to} & x + y & \leq & 7 \\ & -x + 2y & \leq & 4 \\ & x & \geq & 0 \\ & y & \geq & 0 \\ & y & \leq & 4 \end{array} \quad \Rightarrow \quad D = \begin{pmatrix} 1 & 0 \\ 0 & 4 \end{pmatrix} \checkmark$$

Quadratic Programming Application: Low-Risk Investment

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- **Risk-averse strategy:** Maximize the expected return under a given upper bound for the risk!
- **Risk-tolerant strategy:** Minimize the risk under a given lower bound for the expected return!

Quadratic Programming Application: Low-Risk Investment

- Possible **investments:**
  - $1,2,\ldots,n$ (e.g. 1 = Swatch shares, 2 = Credit Suisse shares,...)
- **Investment Characteristics** (not at all easy to know/estimate)**:**
  - R_i : return rate of investment i (assumed to be a random variable)
  - r_i : expected return rate of investment i, $E[R_i]$
  - v_i : variance ("risk") of R_i, $\mathrm{Var}[R_i] := E[(R_i - E[R_i])^2]$
  - v_{ij} : covariance ("correlation") of R_i and R_j, $E[(R_i - E[R_i])(R_j - E[R_j])]$

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$$\boxed{v_{ii} = v_i}$$

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Quadratic Programming Application: Low-Risk Investment

- **Example:** n=2

	r_i
Swatch shares	10% (0.1)
Credit Suisse shares	51% (0.51)

v_{ij}	Swatch shares	Credit Suisse shares
Swatch shares	0.09	-0.05
Credit Suisse shares	-0.05	0.25

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Negative correlation: if CS does worse than expected, Swatch will probably do better, and vice versa

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Read as: standard deviation of return rate is √0.25 = 0.5
(actual return rate could easily be off by 0.5)

Quadratic Programming Application: Low-Risk Investment

- **Investment strategy:**

$$(x_1, x_2, \ldots, x_n), \quad \sum_{i=1}^{n} x_i = 1, \quad x_i \geq 0 \forall i$$

Meaning: An x_i fraction of your money goes into investment *i*

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- **Expected return rate of this strategy:**

$$E[\sum_{i=1}^{n} x_i R_i] = \sum_{i=1}^{n} x_i E[R_i] = \sum_{i=1}^{n} r_i x_i$$

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- **Example:** half the money in Swatch shares, half in Credit Suisse shares; expected return rate is

$$\frac{1}{2} \cdot 0.1 + \frac{1}{2} \cdot 0.51 = 0.305 = 30.5\%$$

Quadratic Programming Application: Low-Risk Investment

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- **Risk of this strategy:**

Straightforward calculations

$$\text{Var}[\sum_{i=1}^{n} x_i R_i] = \sum_{i=1}^{n} \sum_{j=1}^{n} v_{ij} x_i x_j = x^T D x$$

$D = (v_{ij})_{1 \leq i,j \leq n}$ is the *covariance matrix*

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- **Example:** half-half Swatch/CS has risk $\dfrac{0.09 - 2 \cdot 0.05 + 0.25}{4} = 0.06$

Quadratic Programming Application: Low-Risk Investment

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less than each individual risk!

- **Example:** half-half Swatch/CS has risk $\dfrac{0.09 - 2 \cdot 0.05 + 0.25}{4} = 0.06$

Quadratic Programming Application: Low-Risk Investment

- **The risk-tolerant case:** Find the investment strategy with lowest risk that guarantees expected return rate ρ at least!

$$
\boxed{
\begin{aligned}
\text{minimize} \quad & \sum_{i=1}^{n}\sum_{j=1}^{n} v_{ij}x_i x_j \longleftarrow \boxed{\text{risk}} \\
\text{subject to} \quad & \sum_{i=1}^{n} r_i x_i \geq \rho \qquad \boxed{\text{expected return rate}} \\
\boxed{\text{strategy}} \quad & \sum_{i=1}^{n} x_i = 1 \\
& x_i \geq 0, \quad i = 1, \ldots, n
\end{aligned}
}
$$

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\end{aligned}
$$

strategy

Fact: A covariance matrix is positive semidefinite, so this is indeed a convex QP.

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expected return rate

strategy

Fact: A covariance matrix is positive semidefinite, so this is indeed a convex QP.

- **Example:** $\rho = 0.4$: 26.8% Swatch, 73.2% Credit Suisse; risk $= 0.121$

Low-Risk Investment Example ... in CGAL

- **Preamble:** This time, it's floating-point input...

Gnu Multi-precision Library (GMP)

```
#include <iostream>
#include <cassert>
#include <CGAL/basic.h>
#include <CGAL/QP_models.h>
#include <CGAL/QP_functions.h>
#include <CGAL/Gmpzf.h>

// choose exact floating-point type
typedef CGAL::Gmpzf ET;


// program and solution types
typedef CGAL::Quadratic_program<double> Program;
typedef CGAL::Quadratic_program_solution<ET> Solution;
```

Low-Risk Investment Example ... in CGAL

- **Input:** Desired expected return

```
int main() {
  // read minimum expected return rate
  std::cout << "What is your desired expected return rate? ";
  double rho; std::cin >> rho;
```

for example, 0.4 = 40%

Low-Risk Investment Example ... in CGAL

- **Setup:** Make sure to enter matrix *2D* (customary in QP solvers)!

```
// by default, we have a nonnegative QP with Ax >= b
Program qp (CGAL::LARGER, true, 0, false, 0);

// now set the non-default entries:
const int sw = 0;
const int cs = 1;

// constraint on expected return: 0.1 sw + 0.51 cs >= rho
qp.set_a(sw, 0, 0.1);
qp.set_a(cs, 0, 0.51);
qp.set_b(    0, rho);

// strategy constraint: sw + cs = 1
qp.set_a(sw, 1, 1);
qp.set_a(cs, 1, 1);
qp.set_b(    1, 1);
qp.set_r(    1, CGAL::EQUAL); // override default >=

// objective function: 0.09 sw^2 - 0.05 sw cs - 0.05 cs sw + 0.25 cs^2
// we need to specify the entries of the symmetric matrix 2D, on and below the diagonal
qp.set_d(sw, sw,  0.18); //  0.09 sw^2
qp.set_d(cs, sw, -0.10); // -0.05 cs sw
qp.set_d(cs, cs,  0.5);  //  0.25 cs^2
```

$j \leq i$ in `set_d (i, j)`

Low-Risk Investment Example ... in CGAL

- **Setup:** Make sure to enter matrix *2D* (customary in QP solvers)!

```
// by default, we have a QP with Ax >= b
Program qp (CGAL::LARGER, true, 0, false, 0);

// now set the non-default entries:
const int sw = 0;
const int cs = 1;

// constraint on expected return: 0.1 sw + 0.51 cs >= rho
qp.set_a(sw, 0, 0.1);
qp.set_a(cs, 0, 0.51);
qp.set_b(    0, rho);

// strategy constraint: sw + cs = 1
qp.set_a(sw, 1, 1);
qp.set_a(cs, 1, 1);
qp.set_b(    1, 1);
qp.set_r(    1, CGAL::EQUAL); // override default >=

// objective function: 0.09 sw^2 - 0.05 sw cs - 0.05 cs sw + 0.25 cs^2
// we need to specify the entries of the symmetric matrix 2D, on and below the diagonal
qp.set_d(sw, sw,  0.18); //  0.09 sw^2
qp.set_d(cs, sw, -0.10); // -0.05 cs sw
qp.set_d(cs, cs,  0.5);  //  0.25 cs^2
```

⚠ $j \leq i$ in **`set_d (i, j)`**

Low-Risk Investment Example … in CGAL

- **Solve:** ...as nonnegative quadratic program (a little faster)

```
 // solve the program, using ET as the exact type
Solution s = CGAL::solve_nonnegative_quadratic_program(qp, ET());
assert (s.solves_quadratic_program(qp));
```

independent verification

Low-Risk Investment Example ... in CGAL

- **Output:** query solution status; if feasible, output strategy / risk

```
  // output
  if (s.status() == CGAL::QP_INFEASIBLE) {
    std::cout << "Expected return rate " << rho << " cannot be achieved.\n";
  } else {
    assert (s.status() == CGAL::QP_OPTIMAL);
    Solution::Variable_value_iterator opt =
      s.variable_values_begin();
    CGAL::Quotient<ET> sw_fraction = *opt;
    CGAL::Quotient<ET> cs_fraction = *(opt+1);
    std::cout << "Minimum risk investment strategy:\n";
    std::cout << 100.0*CGAL::to_double(sw_fraction)
          << "%" << " into Swatch\n";
    std::cout << 100.0*CGAL::to_double(cs_fraction)
          << "%" << " into Credit Suisse\n";
    std::cout << "Risk = " << CGAL::to_double(s.objective_value()) << "\n";
  }
  return 0;
}
```

Known Bug :=(

- You can't reliably copy or assign instances of the class **CGAL::Quadratic_program_solution<ET>**

- **Workaround 1:** If you want to pass or return such instances to/ from a function, pass a pointer to the instance instead!

- **Workaround 2:** If you want to assign a new solution to an existing instance... don't do it!

Sources and Further Reading

- **LP/QP Solver:** Online manual at **`www.cgal.org`**: Online Manual → Combinatorial Algorithms → Linear and Quadratic Programming Solver

- **Cancer Therapy:** J. O'Rourke, S. Kosaraju, and N. Megiddo: Computing Circular Separabiliy, *Discrete & Computational Geometry* 1:105-113 (1986)

- **Low-Risk Investment:** H. Markowitz: Portfolio Selection, *Journal of Finance* 7(1): 77-91 (1952)