

ORF307 – Optimization

17. Interior-point methods

Ed Forum

- I was confused about the meaning of matrix A
- How does solving a min cost / maxflow problem in this way compare to running the Ford Fulkerson algorithm? Are they similar in terms of complexity, or is one better suited than the other in certain cases?

Recap

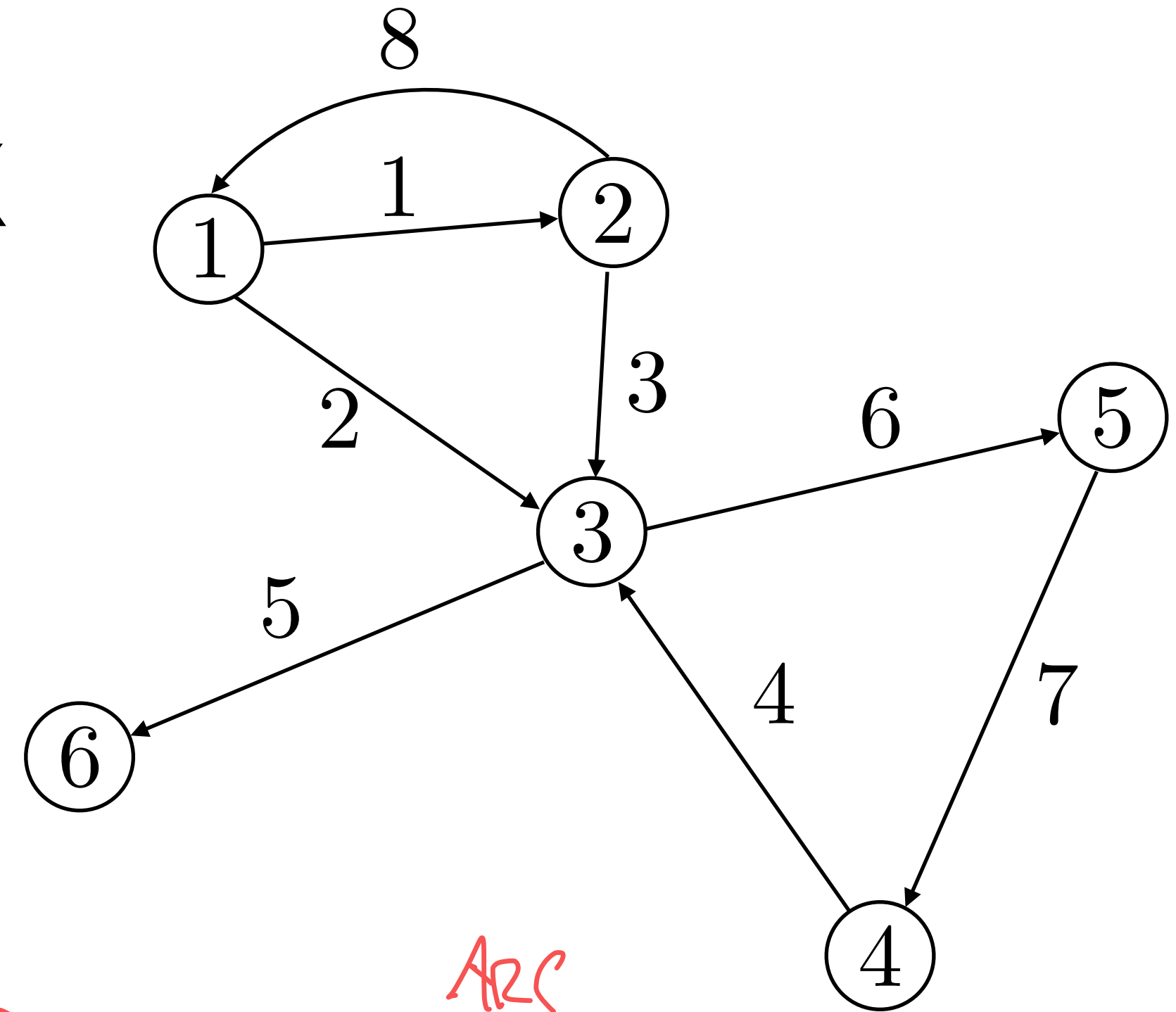
Arc-node incidence matrix

$m \times n$ matrix A with entries

$$A_{ij} = \begin{cases} 1 & \text{if arc } j \text{ starts at node } i \\ -1 & \text{if arc } j \text{ ends at node } i \\ 0 & \text{otherwise} \end{cases}$$

Note Each column has
one -1 and one 1

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Arc

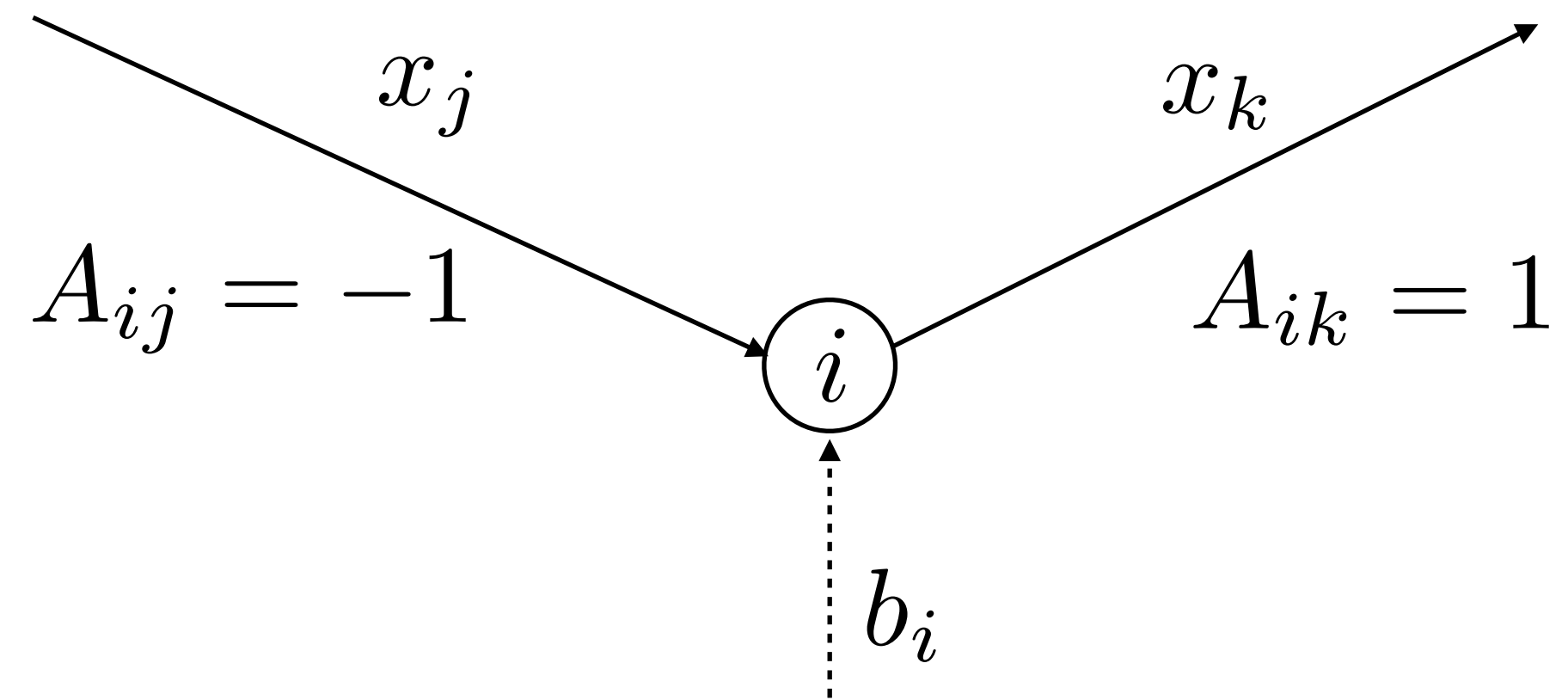
Node

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ -1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & -1 & -1 & -1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}$$

External supply

supply vector $b \in \mathbb{R}^m$

- b_i is the external supply at node i
(if $b_i < 0$, it represents demand)
- We must have $\mathbf{1}^T b = 0$
(total supply = total demand)



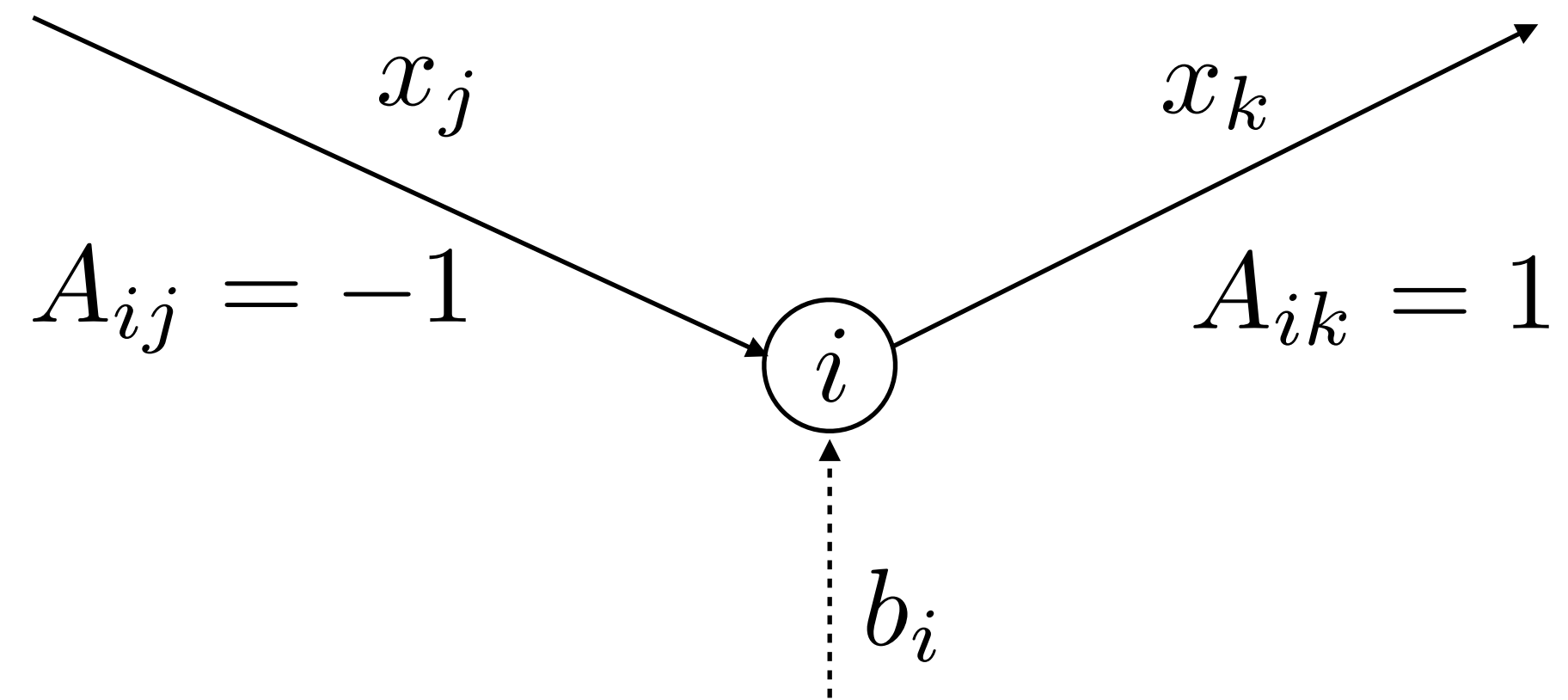
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Balance equations

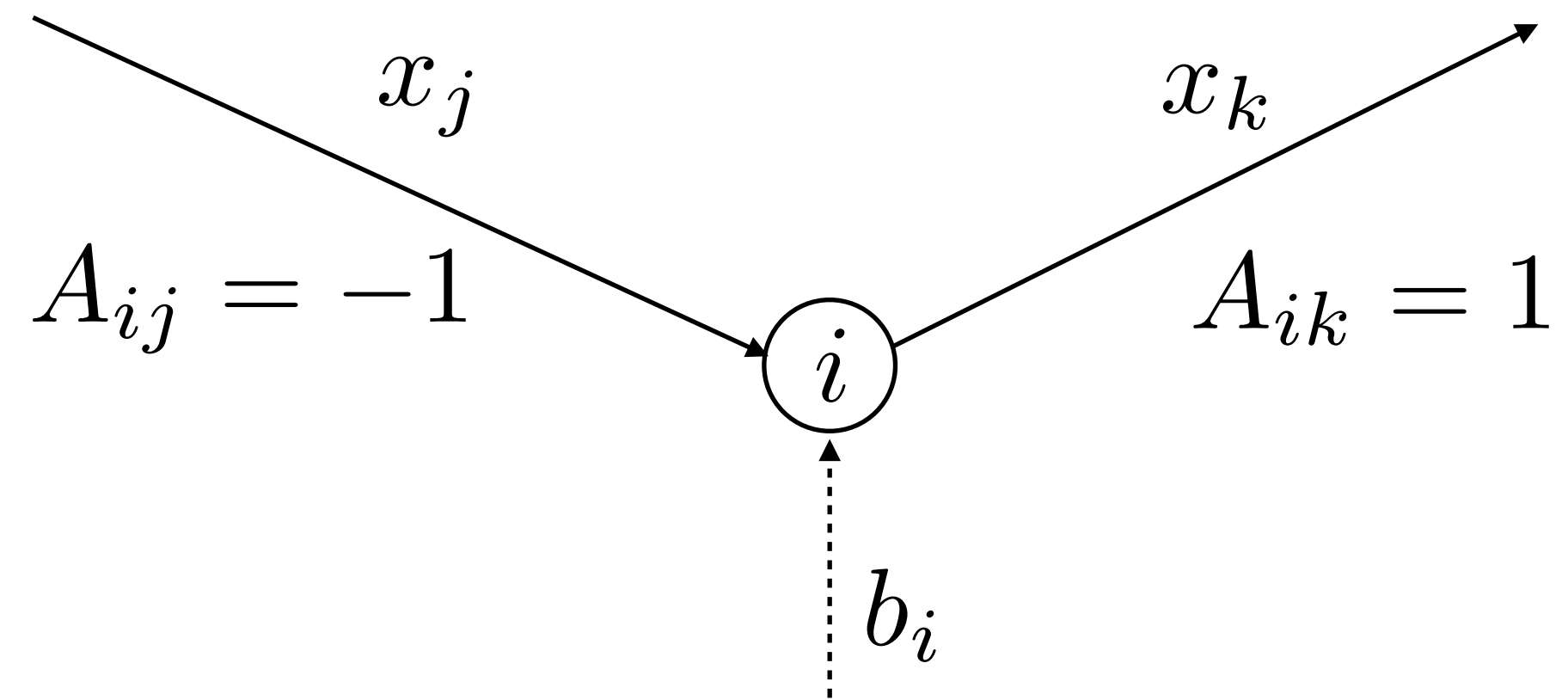
$$\sum_{j=1}^n A_{ij} x_j = (Ax)_i = b_i, \quad \text{for all } i$$



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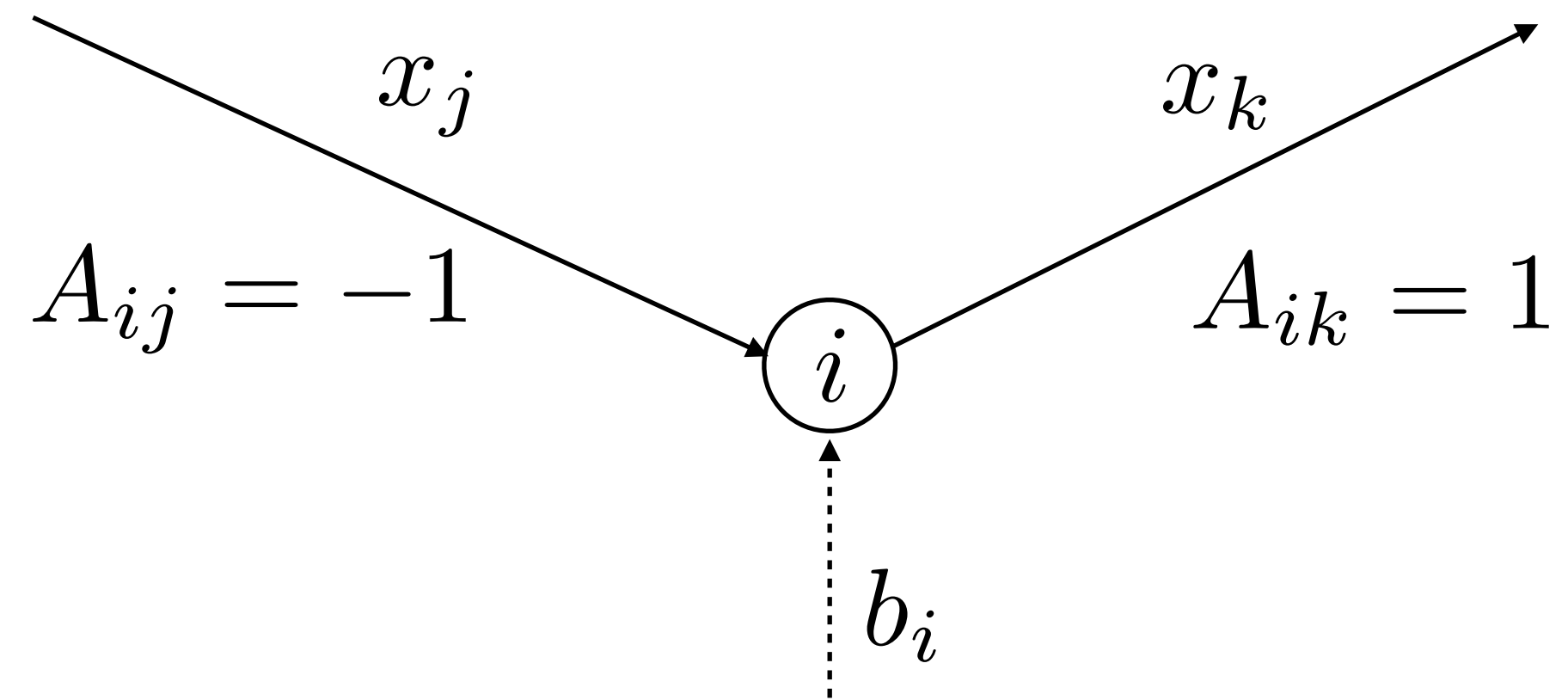
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Total leaving
flow

External supply

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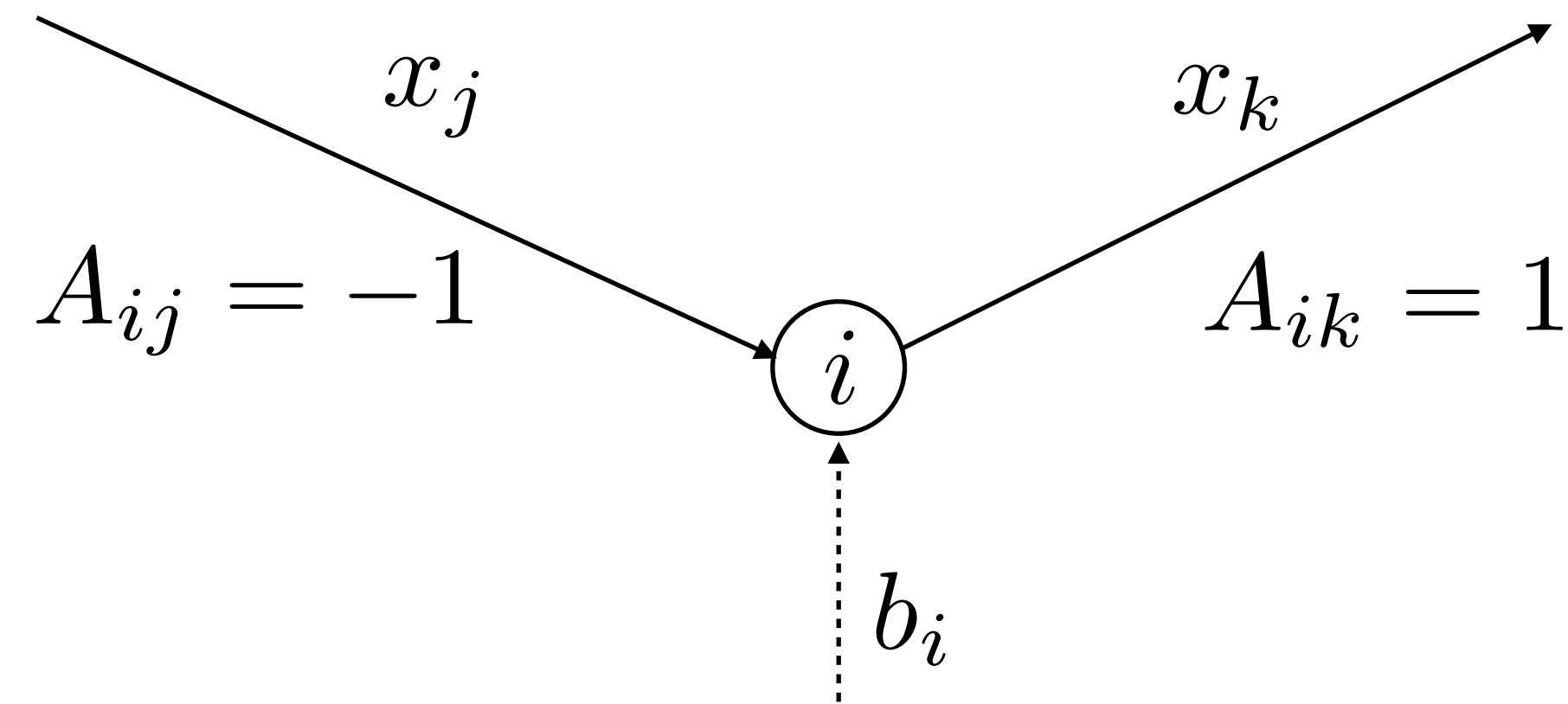
Total leaving flow Supply

External supply

supply vector $b \in \mathbb{R}^m$

- b_i is the external supply at node i (if $b_i < 0$, it represents demand)
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$$-x_j + x_k = b_i$$



Balance equations

$$\sum_{j=1}^n A_{ij} x_j = (Ax)_i = b_i, \quad \text{for all } i$$

Total leaving flow
Supply

$$\longrightarrow Ax = b$$

Minimum cost network flow problem

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax = b \\ & 0 \leq x \leq u \end{array}$$

- c_i is unit cost of flow through arc i
- Flow x_i must be nonnegative
- u_i is the maximum flow capacity of arc i
- Many network optimization problems are just special cases

Integrality theorem

Given a polyhedron $P = \{x \in \mathbf{R}^n \mid Ax = b, \quad x \geq 0\}$

where

- A is totally unimodular
- b is an integer vector



all the extreme points of P are integer vectors.

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-
- all the extreme points of P are integer vectors.

Proof

- All extreme points are basic feasible solutions with $x_B = A_B^{-1}b$ and $x_i = 0, i \neq B$
- A_B^{-1} has integer components because of total unimodularity of A
- b has also integer components
- Therefore, also x is integral



Implications for network and combinatorial optimization

Minimum cost network flow

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If b and u are integral solutions x^* are integral

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Integer linear programs

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Very difficult in general
(more on this in a few weeks)

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If A totally unimodular and b, u integral, we can relax integrality and solve a fast LP instead

Today's lecture

Interior point methods

- History
- Newton's method
- Central path
- Primal-dual path-following algorithm
- Logarithmic barrier functions

History

A brief history of linear optimization

1940s :

- Foundations and applications in economics and logistics (Kantorovich, Koopmans)
- **1947** : Development of the **simplex method** by Dantzig

1950s – 70s:

- Applications expand to engineering, OR, computer science...
- **1975** : Nobel prize in economics for Kantorovich and Koopmans

1980s:

- Development of polynomial time algorithms for LPs
- **1984** : Development of the **interior point method** by Karmarkar

—Today:

- Continued algorithm development. Expansion to very large problems.

Ellipsoid method Khachian (1979)

Answer to major question
Is worst-case LP complexity
polynomial? **Yes!**

Shazam! A Shortcut for Computers

A garment manufacturer has three kinds of dresses — A, B and C. On hand he has 17 bolts of one cloth and 25 of another, as well as 200 buttons and 75 belts. He has three cutters, 10 sewers and one finisher. Dress A, on which he makes a profit of \$1.25 a unit, requires one combination of material, accessories and work; the B dress, with a \$1.50 profit, takes a different combination, and the \$2.25 dress C has yet a third set of requirements. How should he schedule his production to make the most money?

That is an easy example of a kind of eminently practical problem that becomes computationally difficult because of the number of variable factors and constraints that must be handled to get a best solution. And, as the number of variables and restraints grows — as, for instance, in a model of the national economy or in the scheduling of production at any oil refinery — the difficulty mushrooms.

Even the most powerful computers might have to run for hours to tell a plant manager how to handle a small change in, say, the amount of crude oil being delivered to his tanks. And adding one new restriction can substantially increase the number of possible answers and thus the time required to check them for an optimum solution.

Last week, intrigued mathematicians were trying to sort out the meaning of what looked like a stun-

ning theoretical breakthrough in the handling of these “linear programming” problems — and some were wondering why it had taken so long for the breakthrough to become generally known.

In January, the Soviet journal *Doklady* published an abstract of the new solution put forward by a Russian mathematician, L. G. Khachian, about whom no further biographical data has been made public. The abstract was generally overlooked until two mathematicians, working at Stanford University, analyzed the theory and refined its application. Reports of their work and Mr. (or Miss) Khachian’s began appearing in American journals four weeks ago, opening up the floodgates of mathematical curiosity.

Ronald L. Graham, a leading computer expert at the Bell Laboratories in Murray Hill, N.J., said the significance of the new method is that it provides a fast way to test whether there is an optimum solution for any particular linear programming problem and, if there is, to assure that the solution can be computed within a reasonable length of time.

The older, “simplex” method involved having the computer “build” a flat-sided polyhedron in multidimensional space and then hop from vertex to vertex testing for a best answer. Mr. Khachian’s solution has the computer design a multidimensional curved ellipsoid that sur-

rounds the area of possible solutions and is then made smaller until it neatly encloses the optimum answer.

The practical effects of the breakthrough were not entirely clear last week, however. Although it seems to offer enormous advantages in areas ranging from industrial scheduling to weather forecasting, it has yet to be tested in the development of an actual major computer program. Dr. Graham said it might work for some kinds of linear programming problems and not for others, noting that, despite its theoretical limitations, simplex in fact works quite efficiently for the problems it has been asked to handle.

Nevertheless Laslo Lovász, a Hungarian mathematician who worked on the problem at Stanford, said he used the method to program his pocket calculator to solve a problem with six variables and six constraints, which it probably could not have handled with the simplex method. And George B. Dantzig, who devised the simplex method in 1947, said he felt “stupid that I didn’t see” Mr. Khachian’s method.

While some wondered about the delay between the publication of the abstract in *Doklady* and its reception now, others pointed out that “simplex” itself it did not get into wide use until several years after its theoretical formulation.

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Benefits

Motivated new research directions

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Interior-point methods

1980s-1990s: interior point methods

- Karmarkar's algorithm (1984)
- Competitive with simplex, often faster for larger problems
- Began huge effort in algorithm development for convex optimization



SOVIETS HELD TO DELIVER U.S. FAMINE SUPPLIES: In Kambelcha, Ethiopia, west from the United States, a Soviet helicopter is hoisted onto a Soviet helicopter to help relieve emergency. Page A12.

Cocaine Traffickers Kill 17 in Peru Raid On Antidrug Team
 By David F. Mustard
 LIMA, Peru, Nov. 18 — A band of cocaine traffickers burst into a jungle campsite and opened fire with machine guns, killing at least 17 people employed by a United States-financed program to destroy coca crops, the police said today.

All those killed in the attack, which took place early Saturday, were identified as Peruvian employees of the Coca Reduction Organization. The group is taking part in a \$20 million program that the United States is financing to cut the production of coca along the Huastilla River, west more than the illegal coca in Peru's grown.

Vote Comes to a 'Homeland,' But African Problems Linger
 By ALAN COWELL
 Special to The New York Times
 HARARISA, South Africa, Nov. 18 — Under captions that the thought ran and light by turns to places of little hope, the officials and the politicians stood before the gathered iron but that represented a polling booth and said, well, yes, the turnout had been sluggish.

The officials numbered 7 or 8; the voters this day numbered 24, they said from an area of stacks and barrels held that is home to 5,000 people.

Breakthrough in Problem Solving
 By JAMES GLEICK
 A 28-year-old mathematician at A.T.&T. Bell Laboratories has made a startling theoretical breakthrough in the solving of systems of equations that often grow too vast and complex for the most powerful computers.

The discovery, which is to be formally published next month, is already circulating rapidly through the mathematical world. It has also set off a deluge of inquiries from brokerage houses, oil companies and airlines, industries with millions of dollars at stake in problems known as linear programming.

These problems are fiendishly complicated systems, often with thousands of variables. They arise in a variety of commercial and government applications, ranging from allocating time on a communications satellite to routing millions of telephone calls over long distances. Linear programming is particularly useful whenever a limited, expensive resource must be spread most efficiently among competing users. And investment companies use the approach in creating portfolios with the best mix of stocks and bonds.

Faster Solutions Seen
 The Bell Labs mathematician, Dr. Narendra Karmarkar, has devised a radically new procedure that may speed the routine handling of such problems by businesses and Government agencies and also make it possible to tackle problems that are now far out of reach.

"This is a path-breaking result," said Dr. Ronald L. Graham, director of mathematical sciences for Bell Labs in Murray Hill, N.J. "Science has its mo-

AMERICANS IN POLL VIEW GOVERNMENT MORE CONFIDENTLY

But Postelection Inquiry Also Finds Most Think Reagan Will Ask Rise in Taxes

By ADAM CLYMER
 The American public, its level of confidence in government rebounding after more than a decade of doubt, expects President Reagan to avoid an economic recession in his second term and to make a real effort to negotiate an arms control treaty, a New York Times survey finds.

But at the same time, the public expects him to break his most important campaign promise and ask Congress to vote an increase in taxes. Fifty-seven percent of the public and 40 percent of voters expect him to ask for higher taxes.

The poll detailed the depth and tenacity of the national swing toward the Republican Party, showing Americans now about equally divided between those who identify with them and those who identify with the Democrats.

Albany Leaders Predicting a Cut In Income Taxes
 By JOSH BARBANEL
 Republicans and Democrats in Albany predicted yesterday that a cut in personal income taxes similar to that recommended by a Cuomo Administration panel over low revenues seems to be in the cards.

At the same time, however, Republicans said they have had to drop Governor Cuomo "screaming and kicking" into the process. Democrats said the panel's report merely reflected a common sense developed in the Legislature.

The citizens panel, comprising 20 business and civic leaders appointed by Mr. Cuomo, said personal income taxes should be cut by \$15 million a year. This would lower taxes by about 6 percent for most people earning more than \$15,000 and up to 24 percent for those earning less.

Homeless Spend Nights in City Welfare Office
 By SARAH RIMMER
 For the last 10 weeks, homeless families, mostly mothers and young children, have been spending weekend nights on plastic chairs, on counter tops or on the floor in New York City's emergency welfare office because the city's welfare agency has run out of beds.

Other families have been waiting at night through the night while city welfare workers try to find temporary space for them in any of the 12 hotels scattered throughout Manhattan, the Bronx, Brooklyn and Queens that accept emergency welfare cases.

In some cases, the families leave the Manhattan office at 4 or even 5 A.M. for an hour's trip on the subway to hotels in the other boroughs that will receive them to check out as early as 11 A.M. the same morning.

INSIDE
 Tug With 6 Aboard Missing
 A tugboat with six aboard and a large load of scrap iron disappeared on a trip from Bridgeport, Conn., to Port Newark, Page B4.

Musicals for City Opera
 The New York City Opera has received a \$5 million gift for the establishment of a spring musical comedy season starting in 1986. Page C14.

Interview in
 A report said Castro has a TV station in Cuba. Page C11.

ALL-ARMS
 The New York City Police Department is to receive a \$10 million gift for the purchase of 100 new patrol cars. Page C14.

Homeless people waiting at the Emergency Assistance Unit at St. Church Street as city welfare workers try to find temporary space for them.

people are coming to us for three available apartments for them yesterday. "But tonight we're able to say that this is a desperate situation," said Stanley Brumfield, the Deputy architect of homeless families, there is one element that's emerging — more



Senator Bob Dole

TREASURY MAY ASK INCREASES IN TAXES OF SOME CONCERNS

OTHERS COULD PAY LESS
 Depreciation Setup Would be Changed — Little Support in Congress Expected

By DAVID E. ROSENBLUM
 WASHINGTON, Nov. 18 — The Treasury Department is writing a proposal to raise the taxes of some businesses by modifying depreciation rules and reduce the taxes many other companies own by lowering rates over all, according to Reagan Administration officials.

The depreciation proposal is one of many that the Treasury plans to recommend to the White House by Dec. 1. But leading tax specialists in Congress from both parties say there is little appetite for dealing with the kind of tax bill the Administration seems to be preparing.

The Administration plans other discussion would reduce tax rates and simplify the tax code by limiting special write-offs for individuals and corporations but would not continue a reduction in the Federal deficit.

of Little Use to Others
 The system allows large write-offs for companies that invest heavily in real estate, plants and machinery but is of little use to many other companies, such as those in the electronics industry, say some tax specialists.

The centerpiece of the Administration's 1985 business tax code, the depreciation system, is getting the Government's attention. In the last few years in the current fiscal year. According to experts, overall corporate tax rates can be reduced only to the extent

Mr. Cuomo's secretary, Michael J. DeGiulio, said that barring any startling change in the state's fiscal and economic condition, Mr. Cuomo would

Single-Digit Top Rate
 Under the plan, the state's maximum tax rate on married income would drop by 1 percentage point, to 9 percent. In addition, the personal exemption would be raised to \$1,000 from \$800, which would help lower-income workers, and the standard deduction would be set at the Federal level of \$2,300 for a single person and \$2,400 for a married couple.

Even with Congress in adjournment and most legislators on vacation, the politics have begun. Aides to several members of Congress reported stacks of telephone messages from business lobbyists who want to pressure the accelerated depreciation feature of the bill tax cut.

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City officials acknowledged the problem yesterday, and said they were struggling to keep pace with the ever-increasing need for emergency and permanent housing for poor families. This weekend the city opened three additional emergency welfare offices — one each in Brooklyn, Queens and the Bronx — to relieve the pressure at the office at 241 Church Street in lower Manhattan.

As of Oct. 31, 1,176 families who can no longer stay with relatives, or who have been evicted, or whose apartments were in buildings that have burned down, or who have lost their homes for a variety of other reasons were being sheltered by the city in hotels or in its four shelters for families. That is 1,000 more families than a year ago, according to Jack Deacy, a spokesman for the city's Human Resources Administration.

Mr. Deacy said that the city's emergency welfare program was not working as well as it should. He said that the city was planning to open a new emergency welfare office in the Bronx next month.

Breakthrough in Problem Solving

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"This is a path-breaking result," said Dr. Ronald L. Graham, director of mathematical sciences for Bell Labs in Murray Hill, N.J. "Science has its mo-

ments of great progress, and this may well be one of them." Because problems in linear programming can have billions or more possible answers, even high-speed computers cannot check every one. So computers must use a special procedure, an algorithm, to examine as few answers as possible before finding the best one — typically the one that minimizes cost or maximizes efficiency.

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Continued on Page A19, Column 1

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 For the last 10 weeks, homeless families, mostly mothers and young children, have been spending weekend nights on plastic chairs, on counter tops or on the floor in New York City's emergency welfare office because the city's welfare agency has run out of beds.

Other families have been waiting at night through the night while city welfare workers try to find temporary space for them in any of the 12 hotels scattered throughout Manhattan, the Bronx, Brooklyn and Queens that accept emergency welfare cases.

In some cases, the families leave the Manhattan office at 4 or even 5 A.M. for an hour's trip on the subway to hotels in the other boroughs that will receive them to check out as early as 11 A.M. the same morning.

INSIDE
 Tug With 6 Aboard Missing
 A tugboat with six aboard and a large load of scrap iron disappeared on a trip from Bridgeport, Conn., to Port Newark, Page B4.

Musicals for City Opera
 The New York City Opera has received a \$5 million gift for the establishment of a spring musical comedy season starting in 1986. Page C14.

Interview in
 A report said Castro has a TV station in Cuba. Page C11.

ALL-ARMS
 The New York City Police Department is to receive a \$10 million gift for the purchase of 100 new patrol cars. Page C14.

Homeless people waiting at the Emergency Assistance Unit at St. Church Street as city welfare workers try to find temporary space for them.

people are coming to us for three available apartments for them yesterday. "But tonight we're able to say that this is a desperate situation," said Stanley Brumfield, the Deputy architect of homeless families, there is one element that's emerging — more

City officials acknowledged the problem yesterday, and said they were struggling to keep pace with the ever-increasing need for emergency and permanent housing for poor families. This weekend the city opened three additional emergency welfare offices — one each in Brooklyn, Queens and the Bronx — to relieve the pressure at the office at 241 Church Street in lower Manhattan.

As of Oct. 31, 1,176 families who can no longer stay with relatives, or who have been evicted, or whose apartments were in buildings that have burned down, or who have lost their homes for a variety of other reasons were being sheltered by the city in hotels or in its four shelters for families. That is 1,000 more families than a year ago, according to Jack Deacy, a spokesman for the city's Human Resources Administration.

Mr. Deacy said that the city's emergency welfare program was not working as well as it should. He said that the city was planning to open a new emergency welfare office in the Bronx next month.

Newton's method

Newton's root finding method

Goal: solve

$$h(x) = 0$$

Newton's root finding method

Goal: solve

$$h(x) = 0$$

Method

1. Make a guess x^k and a linear approximation

$$h(x) \approx h(x^k) + \frac{\partial h}{\partial x}(x^k)(x - x^k)$$

2. Iteratively set $h(x^k)$ to 0

$$h(x^k) + \frac{\partial h}{\partial x}(x^k)(x^{k+1} - x^k) = 0$$

Newton's method example

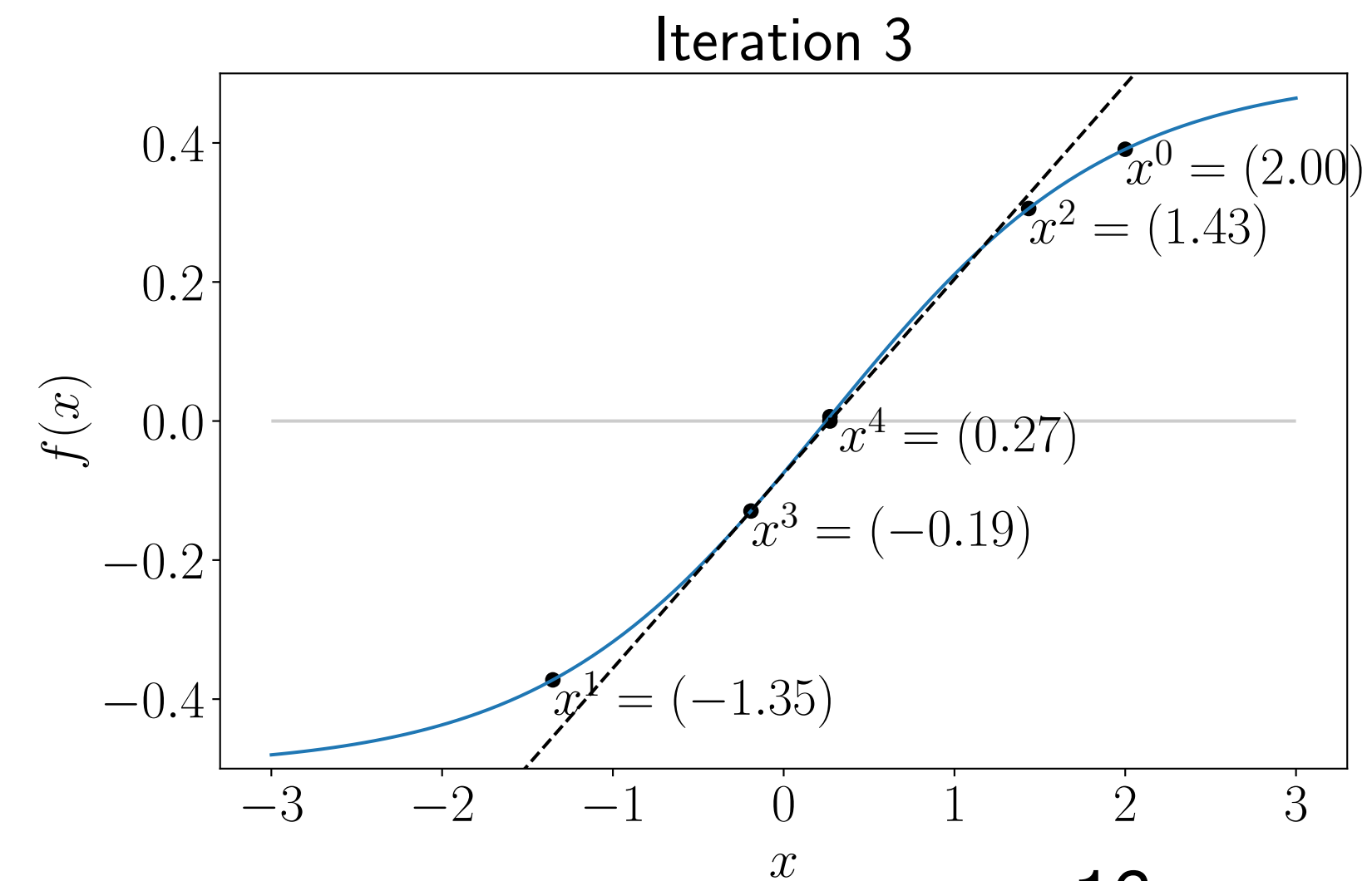
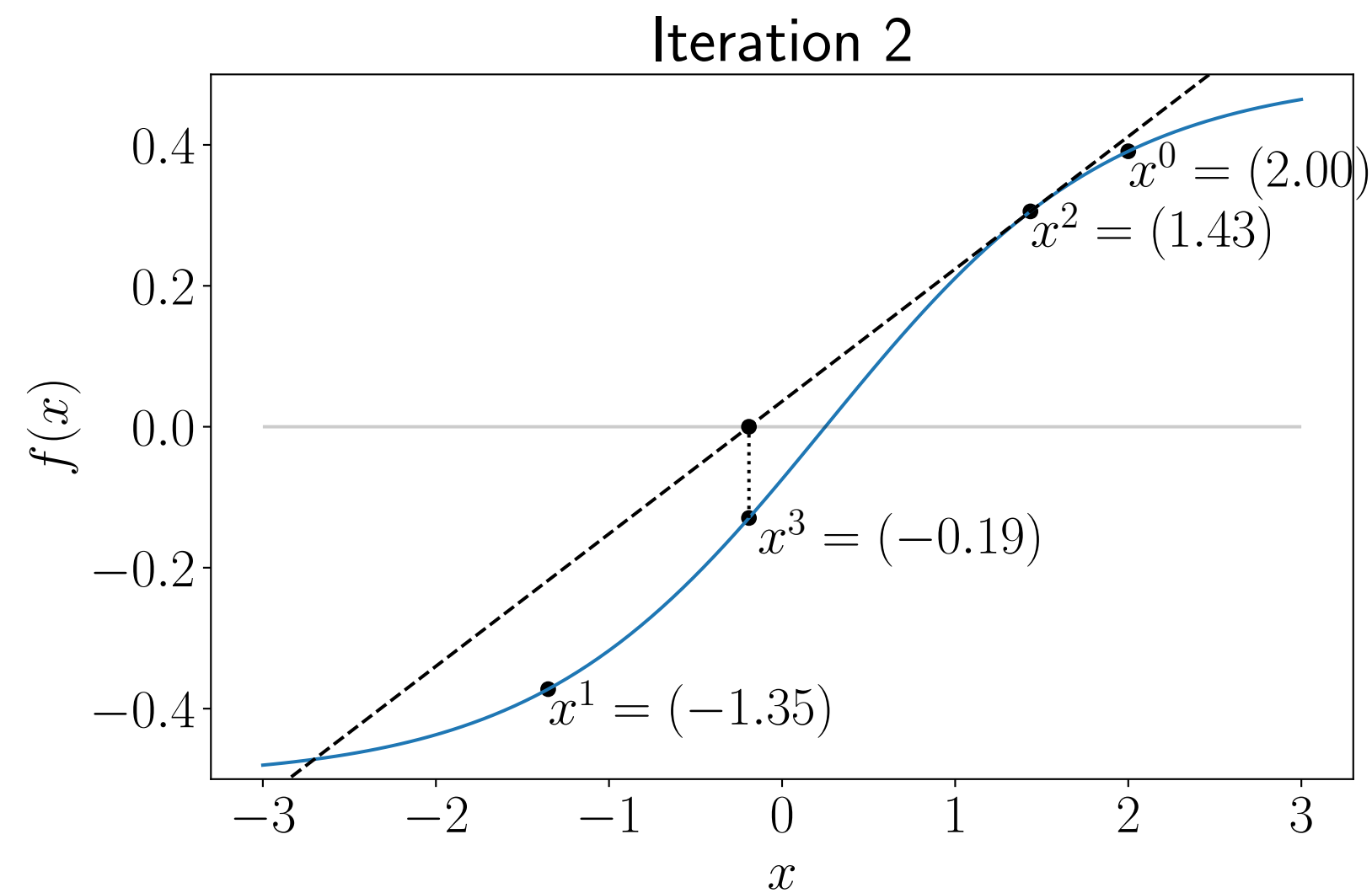
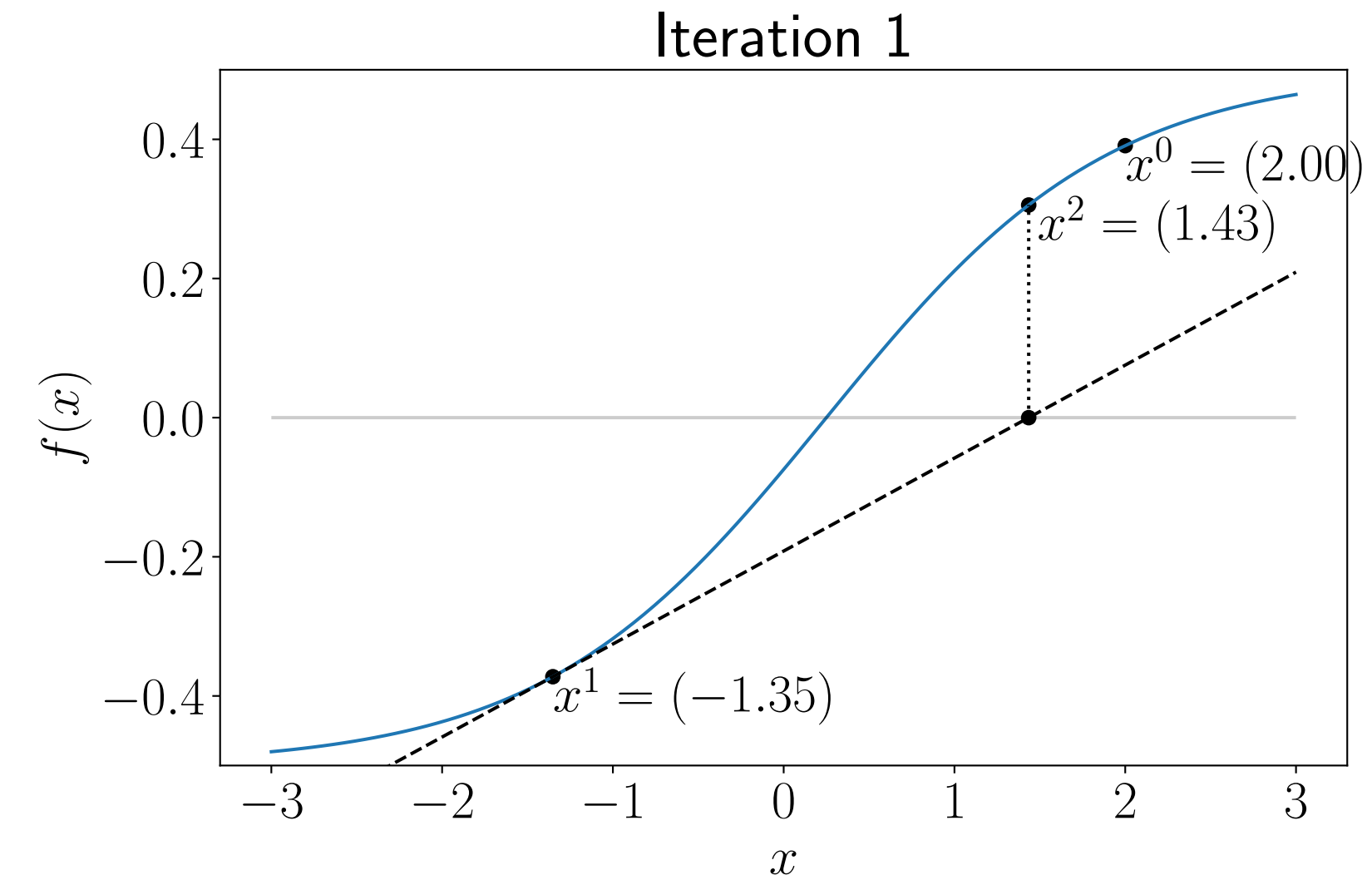
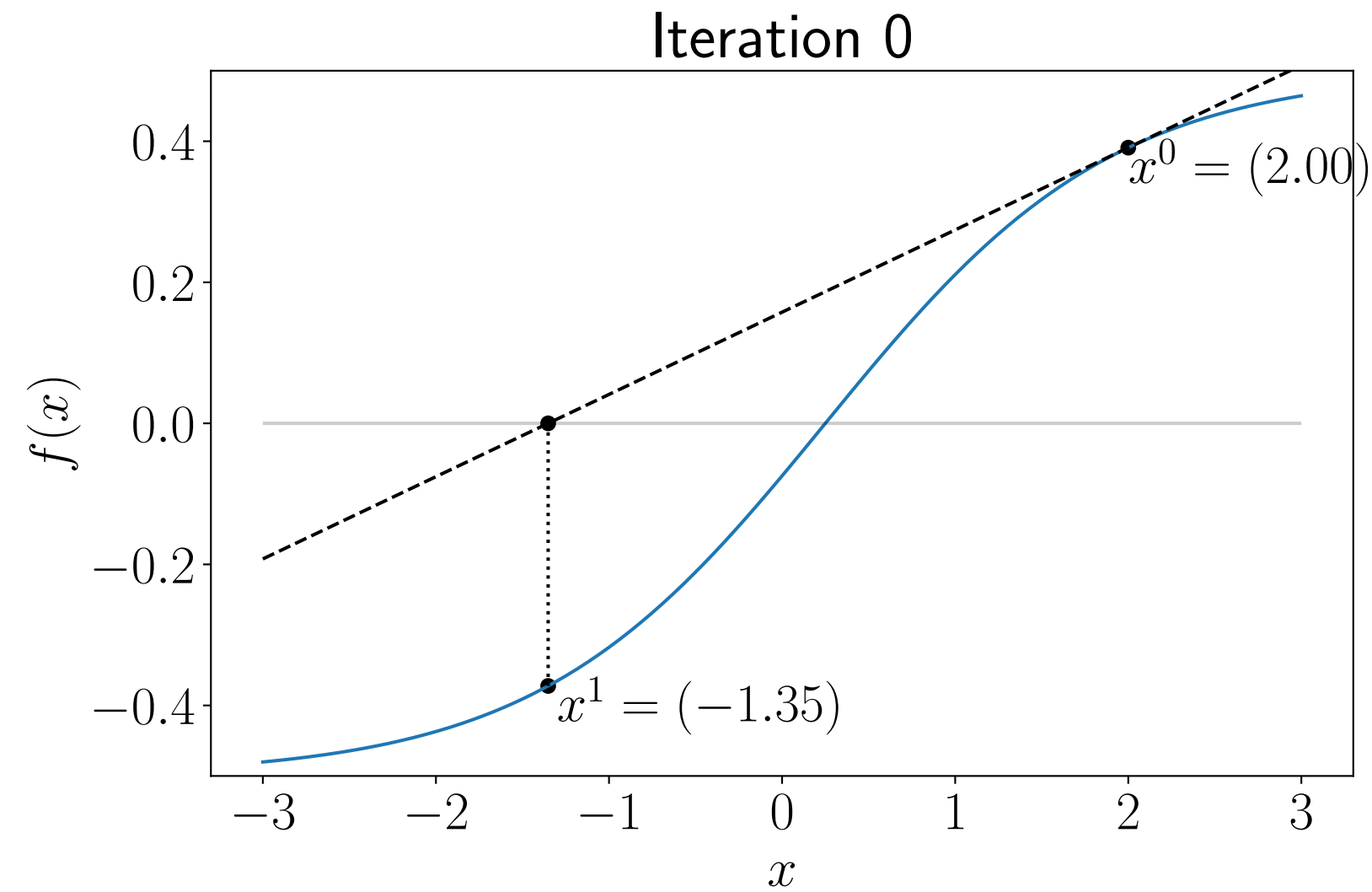
$$x^{k+1} = x^k - f' \nabla f(x^k)$$

$$f(x) = \frac{1}{1 + e^{-1.2x+0.3}} - 0.5$$

$$f(x) = 0$$

↓

$$x^* = 0.3$$



Newton's root finding method (multivariable)

Goal: solve

$$h(x) = 0$$

Newton's root finding method (multivariable)

Goal: solve
 $h(x) = 0$

$$h: \mathbb{R}^n \rightarrow \mathbb{R}^m$$

Method

1. Make a guess x^k and a linear approximation

$$h(x) \approx h(x^k) + Dh(x^k)(x - x^k)$$

2. Iteratively set $h(x^k)$ to 0

$$h(x^k) + Dh(x^k)(x^{k+1} - x^k) = 0$$

Derivative

$$Dh = \begin{bmatrix} \frac{\partial h_1}{\partial x_1} & \cdots & \frac{\partial h_1}{\partial x_n} \\ \vdots & \vdots & \vdots \\ \frac{\partial h_m}{\partial x_1} & \cdots & \frac{\partial h_m}{\partial x_n} \end{bmatrix}$$

Newton method iterations

$$h(x^k) + Dh(x^k)(x^{k+1} - x^k) = 0$$

Newton method iterations

$$h(x^k) + Dh(x^k) \underbrace{(x^{k+1} - x^k)}_{\Delta x} = 0$$

Newton method iterations

$$h(x^k) + Dh(x^k) \underbrace{(x^{k+1} - x^k)}_{\Delta x} = 0$$

Iterations

- Solve $Dh(x^k)\Delta x = -h(x^k)$
- $x^{k+1} \leftarrow x^k + \Delta x$

Newton method iterations

$$h(x^k) + Dh(x^k) \underbrace{(x^{k+1} - x^k)}_{\Delta x} = 0$$

Iterations

- Solve $Dh(x^k)\Delta x = -h(x^k)$
- $x^{k+1} \leftarrow x^k + \Delta x$

Remarks

- Iterations can be **expensive** (linear system solution)
- **Fast convergence** close to the solution x^*

Linear optimization as a root finding problem

Optimality conditions

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

Linear optimization as a root finding problem

Optimality conditions

	Primal	Dual
minimize $c^T x$	minimize $c^T x$	maximize $-b^T y$
subject to $Ax \leq b$	subject to $Ax + s = b$ $s \geq 0$	subject to $A^T y + c = 0$ $y \geq 0$

Linear optimization as a root finding problem

Optimality conditions

	Primal	Dual	
minimize	$c^T x$	maximize	$-b^T y$
subject to	$Ax \leq b$	subject to	$A^T y + c = 0$
	$s \geq 0$		$y \geq 0$

Handwritten notes: A red bracket under b in the primal constraint is labeled m . A red arrow points from b in the primal constraint to b in the primal constraint $Ax + s = b - Ax$. A red circle is drawn around Ax in the primal constraint $Ax + s = b - Ax$.

KKT conditions

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = 0, \quad i = 1, \dots, m$$

$$s, y \geq 0$$

$$s_i = (b - Ax)_i$$

Linear optimization as a root finding problem

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = 0, \quad i = 1, \dots, m$$

$$s, y \geq 0$$

Linear optimization as a root finding problem

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = 0, \quad i = 1, \dots, m$$

$$s, y \geq 0$$

Diagonalize complementary slackness

$$S = \text{diag}(s) = \begin{bmatrix} s_1 & & & \\ & s_2 & & \\ & & \ddots & \\ & & & s_m \end{bmatrix}$$
$$Y = \text{diag}(y) = \begin{bmatrix} y_1 & & & \\ & y_2 & & \\ & & \ddots & \\ & & & y_m \end{bmatrix}$$
$$SY\mathbf{1} = \text{diag}(s)\text{diag}(y)\mathbf{1} = \begin{bmatrix} s_1 y_1 & & & \\ & s_2 y_2 & & \\ & & \ddots & \\ & & & s_m y_m \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} = \begin{bmatrix} s_1 y_1 \\ s_2 y_2 \\ \vdots \\ s_m y_m \end{bmatrix}$$

Linear optimization as a root finding problem

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = 0, \quad i = 1, \dots, m$$

$$s, y \geq 0$$

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$$s_i y_i = 0, \quad i = 1, \dots, m \quad \iff \quad SY\mathbf{1} = 0$$

Main idea

Optimality conditions

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0 \quad \begin{array}{l} S = \text{diag}(s) \\ Y = \text{diag}(y) \end{array}$$

$s, y \geq 0$

- Apply variants of Newton's method to solve $h(\overset{y, x, s}{\cancel{x, s, y}}) = 0$
- Enforce $s, y > 0$ (strictly) at every iteration
- **Motivation** avoid getting stuck in "corners"

Newton's method for optimality conditions

Optimality conditions

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0$$

$s, y \geq 0$

Newton's method for optimality conditions

Optimality conditions

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY \mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY \mathbf{1} \end{bmatrix} = 0$$

$s, y \geq 0$

Derivative

$$Dh(y, x, s) = \begin{bmatrix} \overset{y}{0} & \overset{x}{A} & \overset{s}{I} \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix}$$

Newton's method for optimality conditions

Optimality conditions

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0$$

$s, y \geq 0$

Derivative

$$Dh(y, x, s) = \begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix}$$

Iterations

- Solve $Dh(y^k, x^k, s^k)\Delta(y^k, x^k, s^k) = -h(y^k, x^k, s^k)$

- $$\begin{bmatrix} y^{k+1} \\ x^{k+1} \\ s^{k+1} \end{bmatrix} \leftarrow \begin{bmatrix} y^k \\ x^k \\ s^k \end{bmatrix} + \Delta(y^k, x^k, s^k)$$

Newton's method for optimality conditions

Optimality conditions

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0$$

$s, y \geq 0$

Derivative

$$Dh(y, x, s) = \begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix}$$

Iterations

- Solve $Dh(y^k, x^k, s^k)\Delta(y^k, x^k, s^k) = -h(y^k, x^k, s^k)$

- $\begin{bmatrix} y^{k+1} \\ x^{k+1} \\ s^{k+1} \end{bmatrix} \leftarrow \begin{bmatrix} y^k \\ x^k \\ s^k \end{bmatrix} + \Delta(y^k, x^k, s^k)$

Caution!

It might make (s, y) negative!

Central path

Line search to stay feasible

Root-finding equation

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0$$

Linear system

$$\begin{matrix} Dh \\ \begin{bmatrix} 0 \\ A^T \\ S \end{bmatrix} \end{matrix} \begin{bmatrix} A & I & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -h \\ -r_p \\ -r_d \\ -SY\mathbf{1} \end{bmatrix}$$

Residuals

$$r_p = Ax + s - b$$

$$r_d = A^T y + c$$

Line search to stay feasible

Root-finding equation

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0$$

Linear system

$$\begin{matrix} Dh & & -h \\ \begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} & \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} & = \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} \end{bmatrix} \end{matrix}$$

Residuals

$$r_p = Ax + s - b$$

$$r_d = A^T y + c$$

Line search to enforce $s, y > 0$

$$(y, x, s) \leftarrow (y, x, s) + \alpha(\Delta y, \Delta x, \Delta s)$$

Line search to stay feasible

Root-finding equation

$$h(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} \end{bmatrix} = \begin{bmatrix} r_p \\ r_d \\ SY\mathbf{1} \end{bmatrix} = 0$$

Linear system

$$\begin{matrix} Dh \\ \begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \end{matrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{matrix} -h \\ \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} \end{bmatrix} \end{matrix}$$

Residuals

$$r_p = Ax + s - b$$

$$r_d = A^T y + c$$

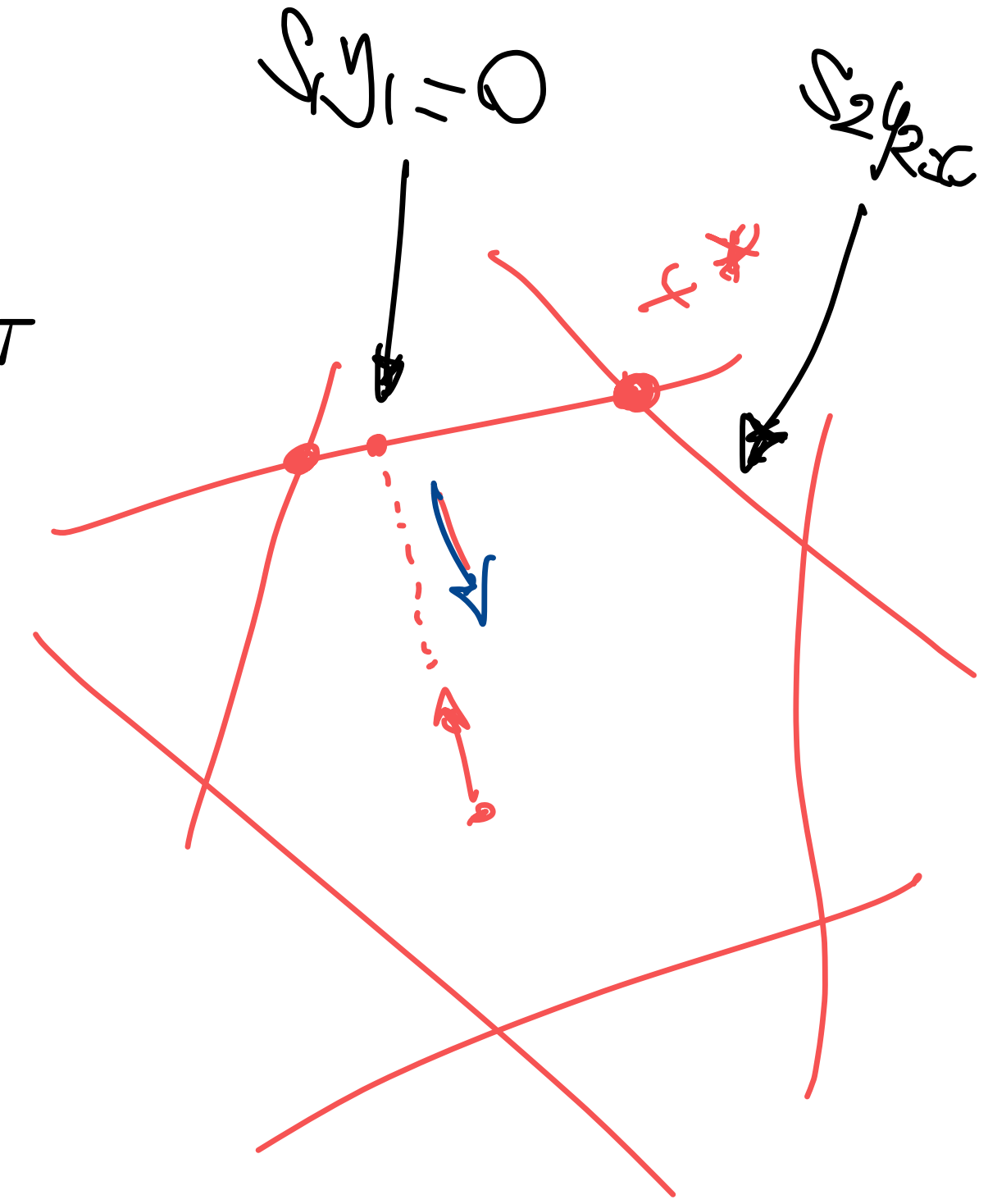
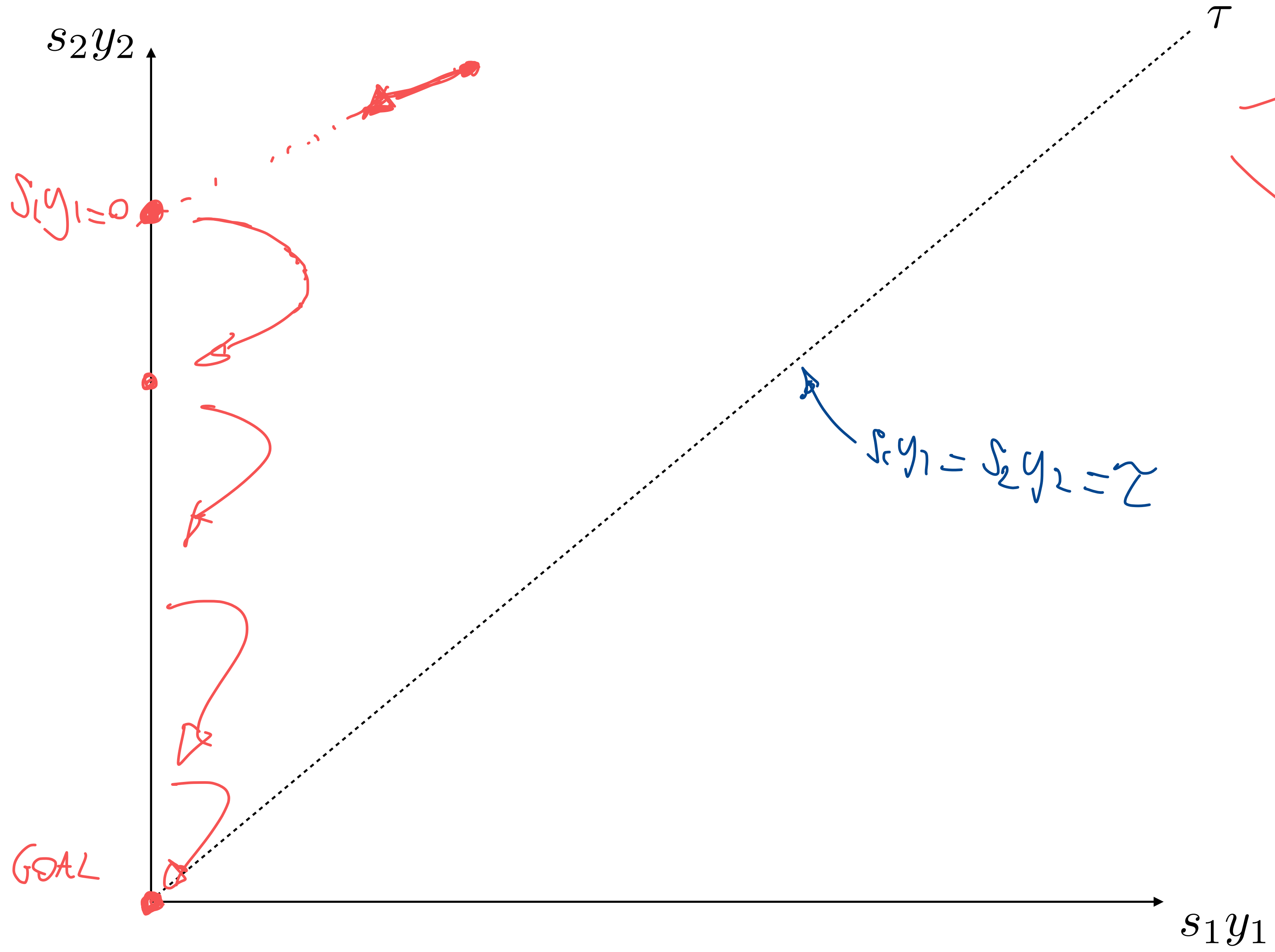
Issue

Pure **Newton's step** does not allow significant progress towards

$$h(y, x, s) = 0 \text{ and } s, y \geq 0.$$

Line search to enforce $s, y > 0$
 $(y, x, s) \leftarrow (y, x, s) + \alpha(\Delta y, \Delta x, \Delta s)$

The central path



$s_1y_1 = 0$
 $s_2y_2 = 0$
 \vdots
 \vdots
 \vdots
 $s_m y_m = 0$

Smoothed optimality conditions

Optimality conditions

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = \tau \longleftarrow \text{Same } \tau \text{ for every pair}$$

$$s, y \geq 0$$

Same optimality conditions for a “smoothed” version of our problem

Smoothed optimality conditions

Optimality conditions

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = \tau \longleftarrow \text{Same } \tau \text{ for every pair}$$

$$s, y \geq 0$$

Same optimality conditions for a “smoothed” version of our problem

Duality gap

$$m \tau = s^T y = (b - Ax)^T y = b^T x - x^T A^T y = b^T y + c^T x$$

Newton's method for smoothed optimality conditions

Smoothed optimality conditions

$$h_{\tau}(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} - \tau\mathbf{1} \end{bmatrix} = 0$$
$$s, y \geq 0$$

Newton's method for smoothed optimality conditions

Smoothed optimality conditions

$$h_\tau(y, x, s) = \begin{bmatrix} Ax + s - b \\ A^T y + c \\ SY\mathbf{1} - \tau\mathbf{1} \end{bmatrix} = 0$$

$$s, y \geq 0$$

Linear system

$$\begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -r_p \\ -r_d \\ -SY + \tau\mathbf{1} \end{bmatrix}$$

Line search to enforce $s, y > 0$

$$(y, x, s) \leftarrow (y, x, s) + \alpha(\Delta y, \Delta x, \Delta s)$$

The path parameter

Duality measure

$$\mu = \frac{s^T y}{m} \quad (\text{average value of the pairs } s_i y_i)$$

The path parameter

Duality measure

$$\mu = \frac{s^T y}{m} \quad (\text{average value of the pairs } s_i y_i)$$

Linear system

$$\begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} + \sigma\mu\mathbf{1} \end{bmatrix}$$

The path parameter

Duality measure

$$\mu = \frac{s^T y}{m} \quad (\text{average value of the pairs } s_i y_i)$$

Linear system

$$\begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} + \sigma\mu\mathbf{1} \end{bmatrix}$$

Centering parameter

$$\sigma \in [0, 1]$$

The path parameter

Duality measure

$$\mu = \frac{s^T y}{m} \quad (\text{average value of the pairs } s_i y_i)$$

Linear system

$$\begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} + \sigma\mu\mathbf{1} \end{bmatrix}$$

Centering parameter

$$\sigma \in [0, 1]$$

$$\sigma = 0$$

\Rightarrow

Newton step

$$\sigma = 1$$

\Rightarrow

Centering step towards $(y^*(\mu), x^*(\mu), s^*(\mu))$

The path parameter

Duality measure

$$\mu = \frac{s^T y}{m} \quad (\text{average value of the pairs } s_i y_i)$$

Linear system

$$\begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} + \sigma\mu\mathbf{1} \end{bmatrix}$$

Centering parameter

$$\sigma \in [0, 1]$$

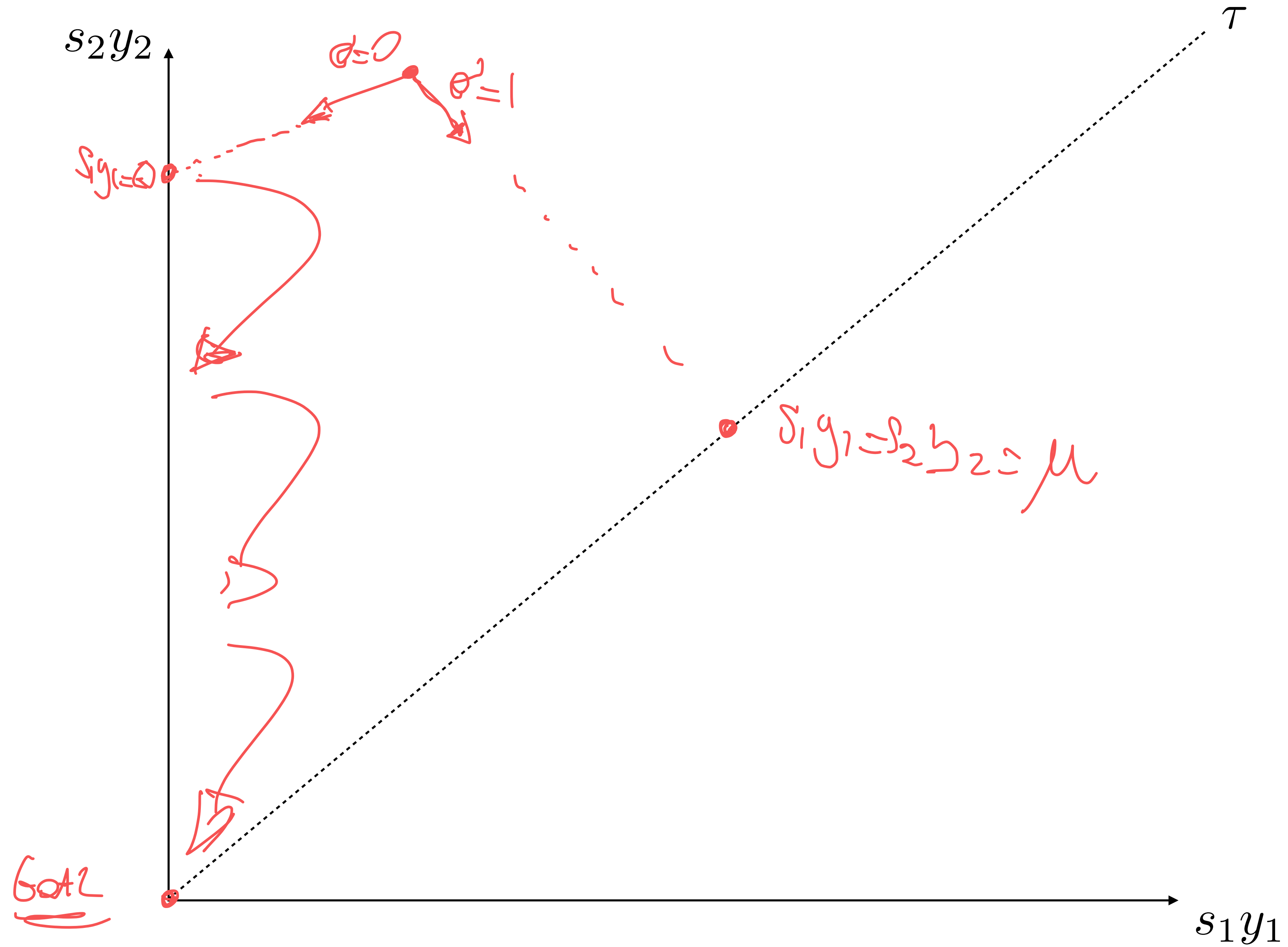
$\sigma = 0 \Rightarrow$ Newton step

$\sigma = 1 \Rightarrow$ Centering step towards $(y^*(\mu), x^*(\mu), s^*(\mu))$

Line search to enforce $s, y > 0$

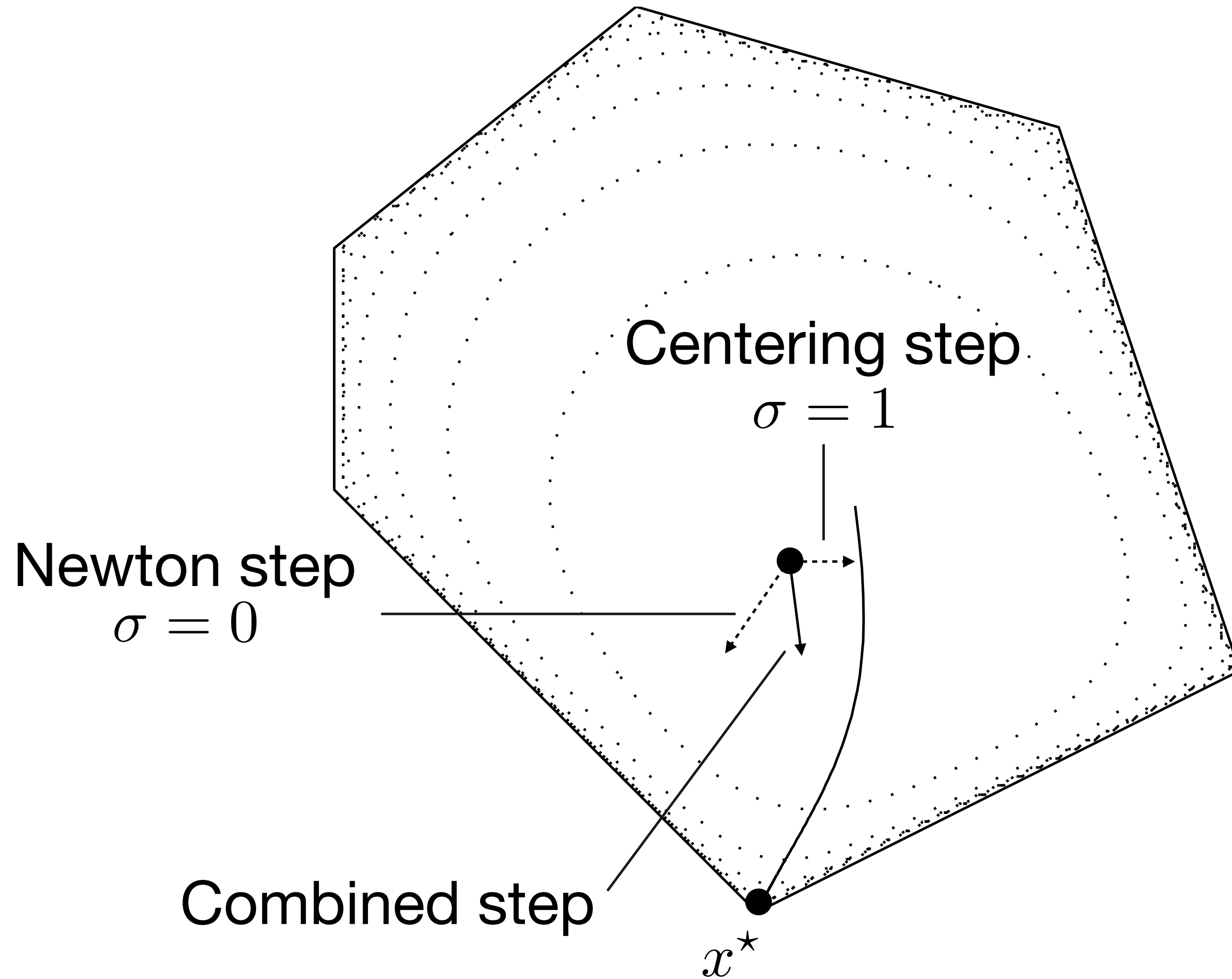
$$(y, x, s) \leftarrow (y, x, s) + \alpha(\Delta y, \Delta x, \Delta s)$$

The central path

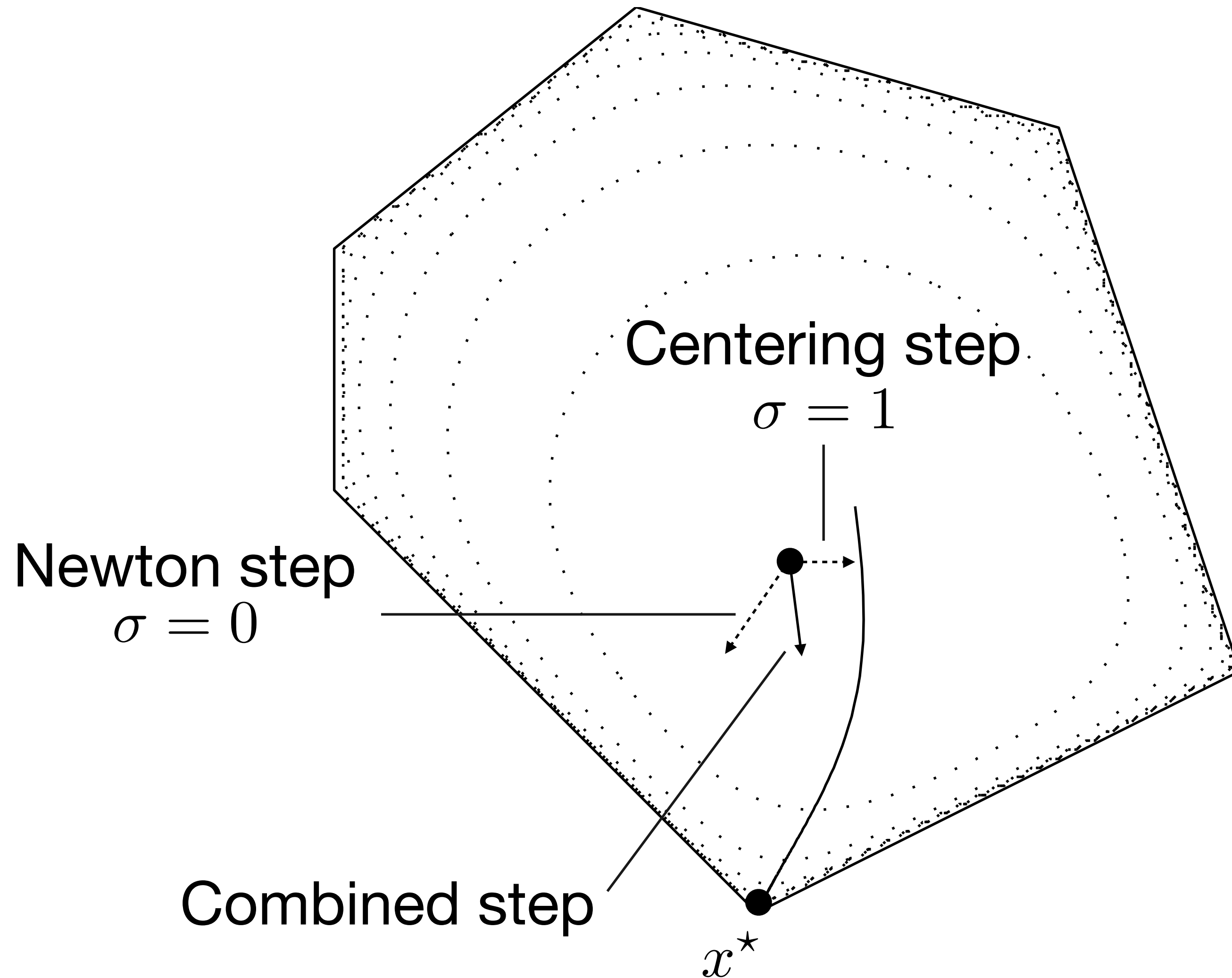


Primal-dual path-following method

Path-following algorithm idea



Path-following algorithm idea

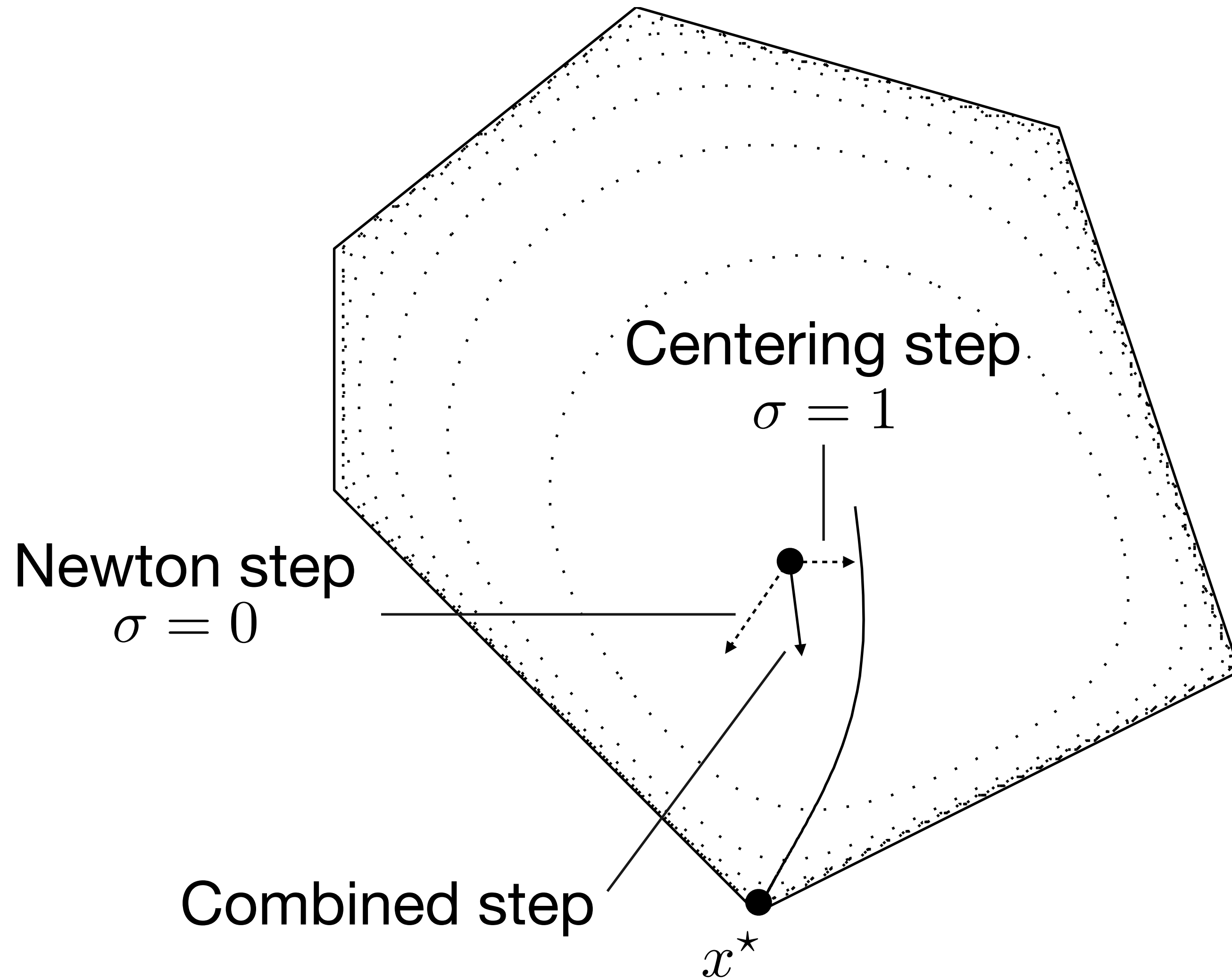


Centering step

It brings towards the **central path** and is usually biased towards $s, y > 0$.

No progress on duality measure μ

Path-following algorithm idea



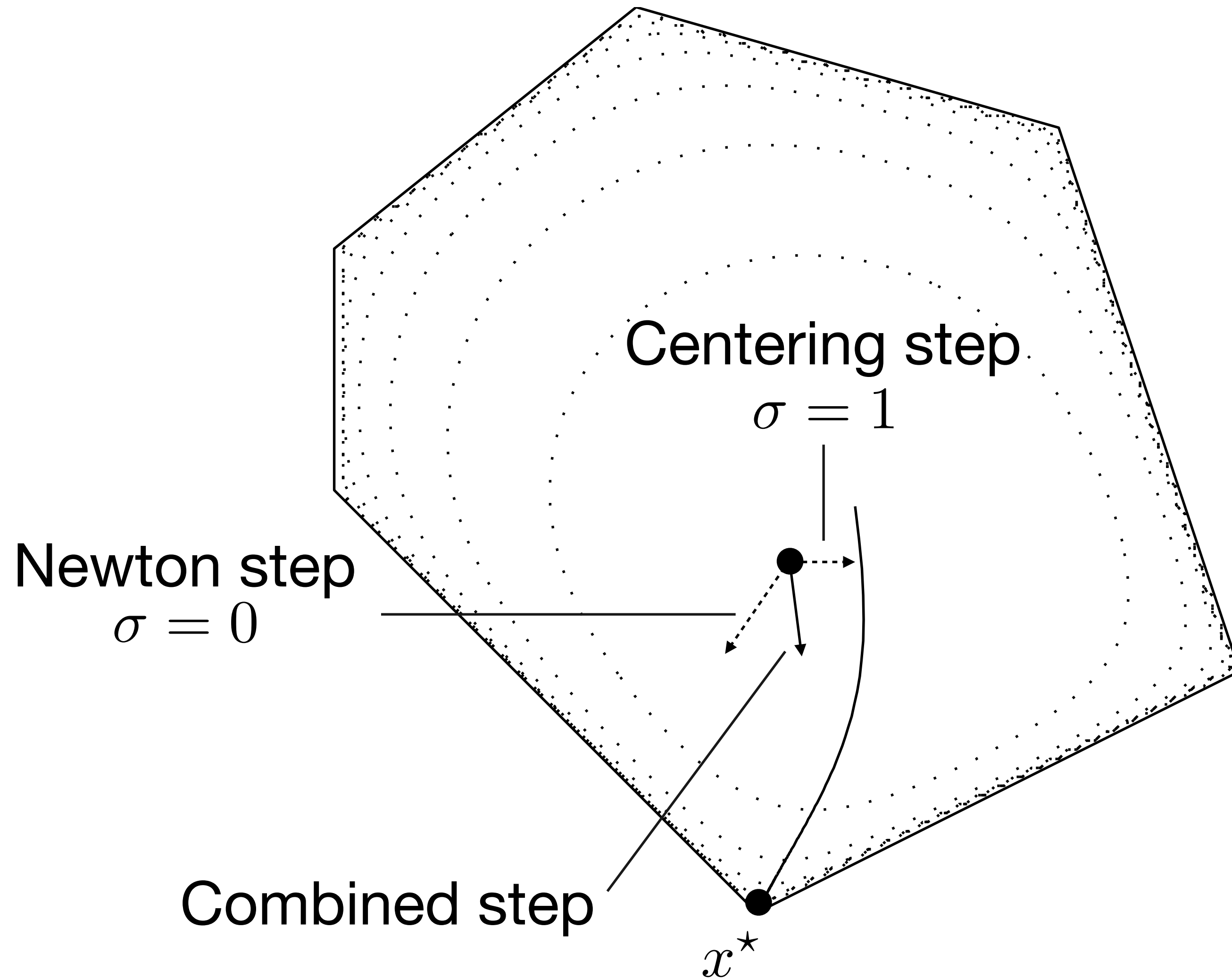
Centering step

It brings towards the **central path** and is usually biased towards $s, y > 0$.
No progress on duality measure μ

Newton step

It brings towards the **zero duality measure** μ . Quickly violates $s, y > 0$.

Path-following algorithm idea



Centering step

It brings towards the **central path** and is usually biased towards $s, y > 0$.
No progress on duality measure μ

Newton step

It brings towards the **zero duality measure** μ . Quickly violates $s, y > 0$.

Combined step

Best of both worlds with longer steps

Primal-dual path-following algorithm

Initialization

1. Given (x_0, s_0, y_0) such that $s_0, y_0 > 0$

Iterations

1. Choose $\sigma \in [0, 1]$

2. Solve
$$\begin{bmatrix} 0 & A & I \\ A^T & 0 & 0 \\ S & 0 & Y \end{bmatrix} \begin{bmatrix} \Delta y \\ \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} -r_p \\ -r_d \\ -SY\mathbf{1} + \sigma\mu\mathbf{1} \end{bmatrix} \text{ where } \mu = s^T y / m$$

3. Find maximum α such that $y + \alpha\Delta y > 0$ and $s + \alpha\Delta s > 0$

4. Update $(y, x, s) \leftarrow (y, x, s) + \alpha(\Delta y, \Delta x, \Delta s)$

Working towards optimality conditions

Optimality conditions satisfied **only at convergence**

Primal residual

$$r_p = Ax + s - b \rightarrow 0$$

Dual residual

$$r_d = A^T y + c \rightarrow 0$$

Complementary slackness

$$s^T y \rightarrow 0$$

Working towards optimality conditions

Optimality conditions satisfied **only at convergence**

Primal residual

$$r_p = Ax + s - b \rightarrow 0$$

Dual residual

$$r_d = A^T y + c \rightarrow 0$$

Complementary slackness

$$s^T y \rightarrow 0$$

Stopping criteria

$$\|r_p\| \leq \epsilon_{\text{pri}}$$

$$\|r_d\| \leq \epsilon_{\text{dua}}$$

$$s^T y \leq \epsilon_{\text{gap}}$$

Logarithmic barrier functions

Smoothed optimality conditions

Optimality conditions

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = \tau \longleftarrow \text{Same } \tau \text{ for every pair}$$

$$s, y \geq 0$$

Same optimality conditions for a “smoothed” version of our problem

Smoothed optimality conditions

Optimality conditions

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = \tau \longleftarrow \text{Same } \tau \text{ for every pair}$$

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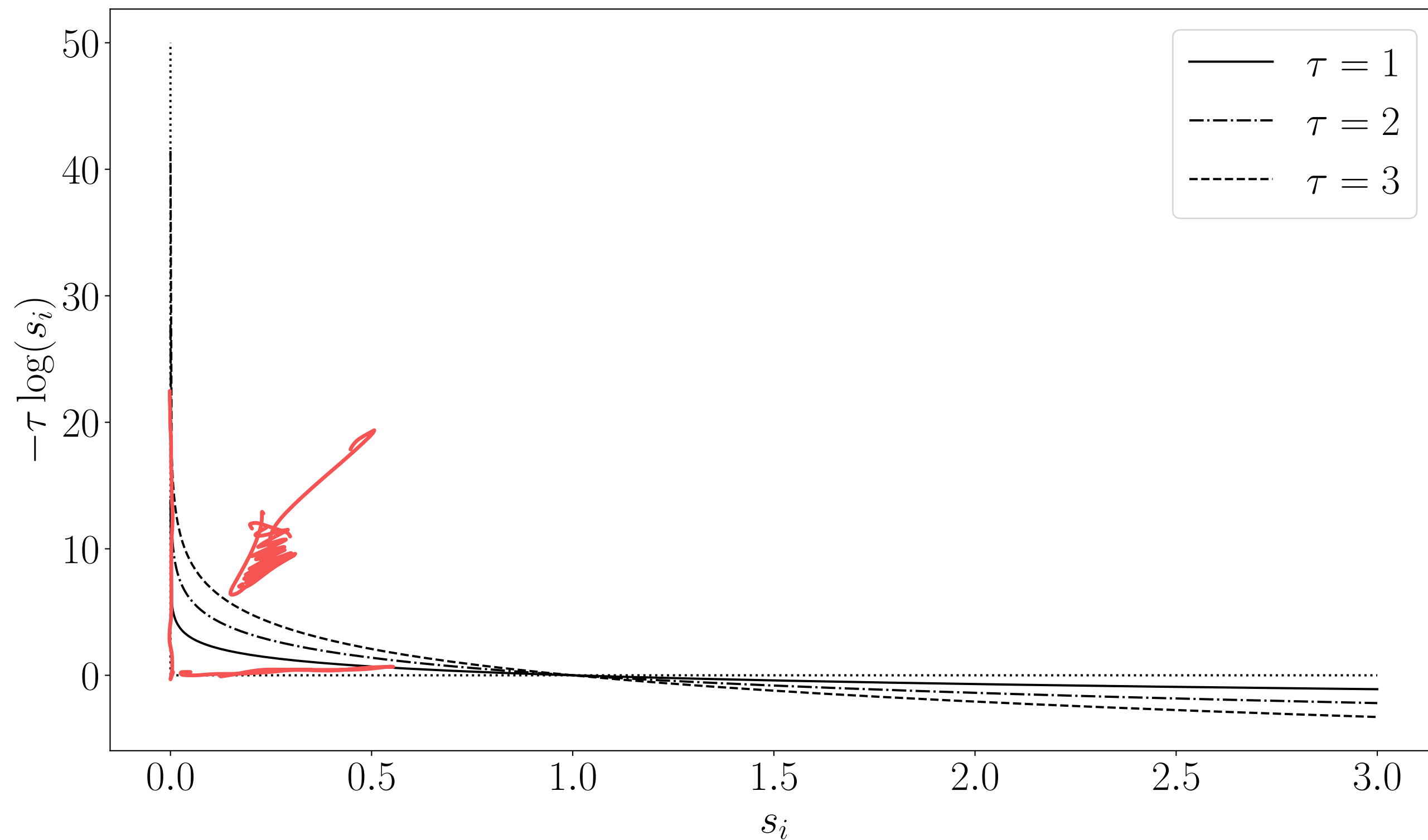
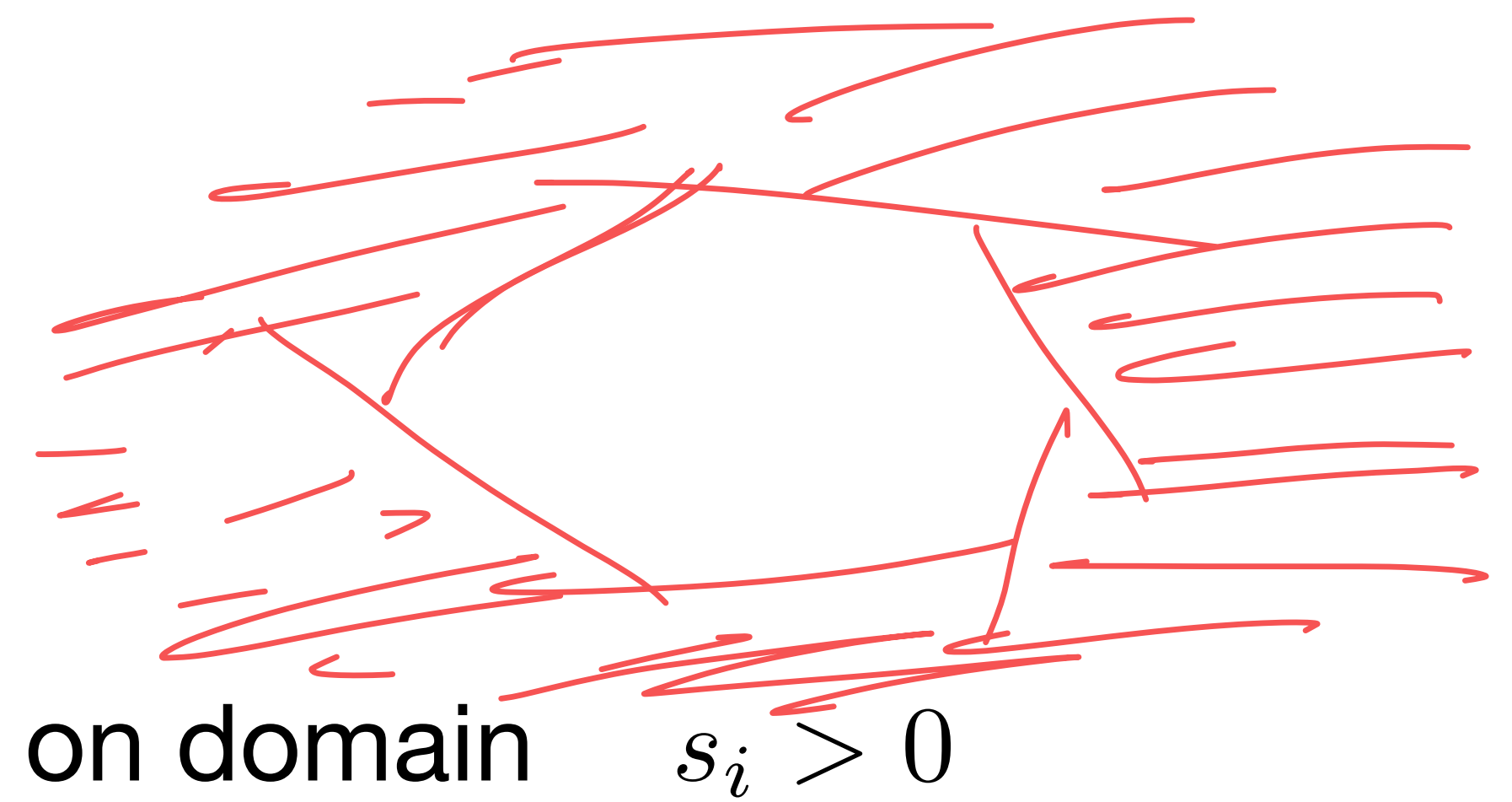
Same optimality conditions for a “smoothed” version of our problem

Do solutions actually exist?

What do they represent?

Logarithmic barrier

$$\phi(s) = -\tau \sum_{i=1}^m \log(s_i)$$



As $\tau \rightarrow 0$ it approximates

$$\mathcal{I}_{s_i \geq 0} = \begin{cases} 0 & \text{if } s_i \geq 0 \\ \infty & \text{otherwise} \end{cases}$$

Smoothed problem

minimize $c^T x$

subject to $Ax + s = b$

$s \geq 0$

Smoothed problem

$$\begin{array}{l} \text{minimize} \quad c^T x \\ \text{subject to} \quad Ax + s = b \\ \quad \quad \quad s \geq 0 \end{array} \longrightarrow \begin{array}{l} \text{minimize} \quad c^T x + \phi(s) = c^T x - \tau \sum_{i=1}^m \log(s_i) \\ \text{subject to} \quad Ax + s = b \end{array}$$

Smoothed problem

$$\begin{array}{l} \text{minimize} \quad c^T x \\ \text{subject to} \quad Ax + s = b \\ \quad \quad \quad s \geq 0 \end{array} \longrightarrow \begin{array}{l} \text{minimize} \quad c^T x + \phi(s) = c^T x - \tau \sum_{i=1}^m \log(s_i) \\ \text{subject to} \quad Ax + s = b \quad (y) \end{array}$$

Lagrangian function

$$L(x, s, y) = c^T x - \tau \sum_{i=1}^m \log(s_i) + y^T (Ax + s - b)$$

Smoothed problem

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax + s = b \\ & s \geq 0 \end{array} \longrightarrow \begin{array}{ll} \text{minimize} & c^T x + \phi(s) = c^T x - \tau \sum_{i=1}^m \log(s_i) \\ \text{subject to} & Ax + s = b \end{array}$$

Lagrangian function

$$L(x, s, y) = c^T x - \tau \sum_{i=1}^m \log(s_i) + y^T (Ax + s - b)$$

$$\frac{\partial L}{\partial x} = A^T y + c = 0$$

$$\frac{\partial L}{\partial s_i} = -\tau \frac{1}{s_i} + y_i = 0 \implies s_i y_i = \tau$$

Central path

$$\begin{aligned} \text{minimize} \quad & c^T x - \tau \sum_{i=1}^m \log(s_i) \\ \text{subject to} \quad & Ax + s = b \end{aligned}$$

Set of points $(x^*(\tau), s^*(\tau), y^*(\tau))$
with $\tau > 0$ such that

$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = \tau$$

$$s, y \geq 0$$

Central path

$$\begin{aligned} &\text{minimize} && c^T x - \tau \sum_{i=1}^m \log(s_i) \\ &\text{subject to} && Ax + s = b \end{aligned}$$

Set of points $(x^*(\tau), s^*(\tau), y^*(\tau))$
with $\tau > 0$ such that

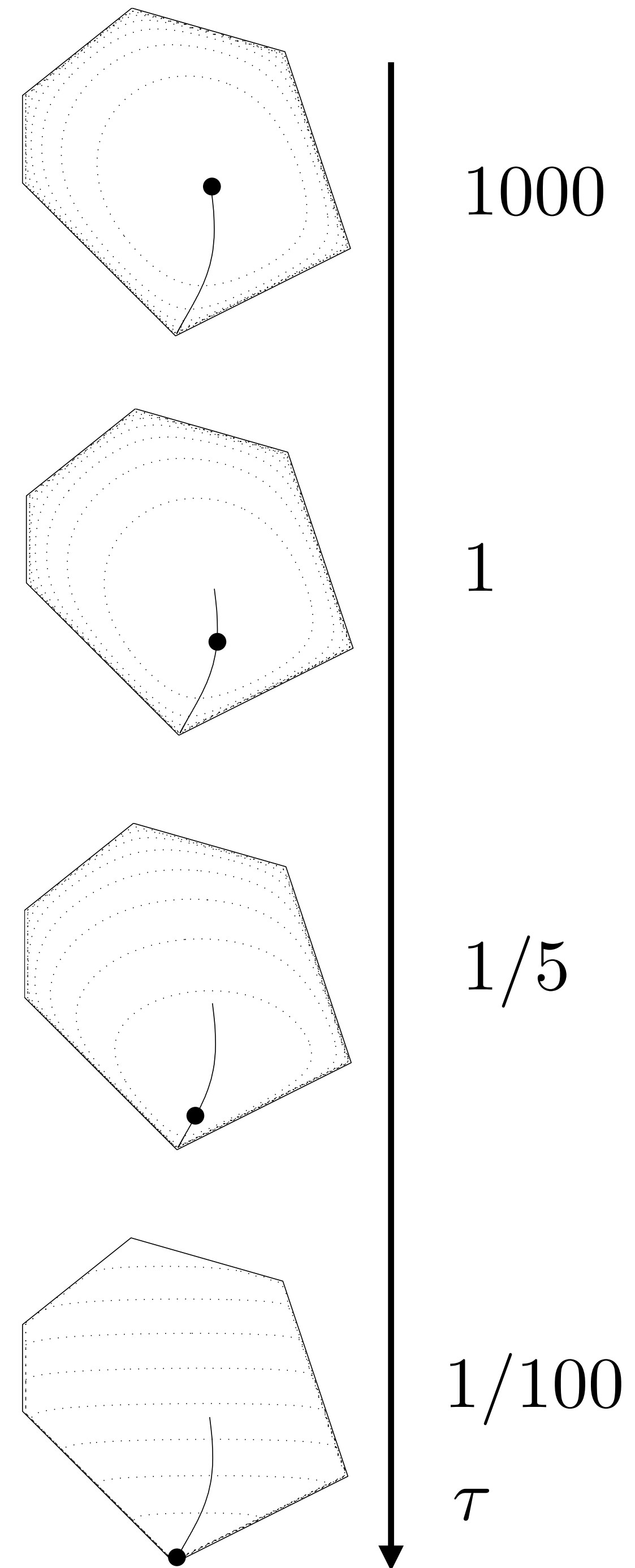
$$Ax + s - b = 0$$

$$A^T y + c = 0$$

$$s_i y_i = \tau$$

$$s, y \geq 0$$

**Analytic
Center**
 $\tau \rightarrow \infty$



Main idea

Follow central path as $\tau \rightarrow 0$

Interior-point methods for linear optimization

Today, we learned to:

- **Apply** Newton's method to solve optimality conditions
- **Follow** the central path and the smoothed optimality conditions
- **Use logarithmic barrier functions** to interpret central path steps

References

- D. Bertsimas and J. Tsitsiklis: Introduction to Linear Optimization
 - Chapter 9.4 — 9.6: Interior point methods
- R. Vanderbei: Linear Programming
 - Chapter 17: The Central Path
 - Chapter 15: A Path-Following Method

Next lecture

- Practical interior-point method (Mehrotra predictor-corrector algorithm)
- Implementation details
- Interior-point vs simples