

# Math (P)refresher for Political Scientists\*

Harvard University

2016

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\*The documents in this booklet are the product of generations of Math (P)refresher Instructors: Curt Signorino 1996-1997; Ken Scheve 1997-1998; Eric Dickson 1998-2000; Orit Kedar 1999; James Fowler 2000-2001; Kosuke Imai 2001-2002; Jacob Kline 2002; Dan Epstein 2003; Ben Ansell 2003-2004; Ryan Moore 2004-2005; Mike Kellermann 2005-2006; Ellie Powell 2006-2007; Jen Katkin 2007-2008; Patrick Lam 2008-2009; Viridiana Rios 2009-2010; Jennifer Pan 2010-2011; Konstantin Kashin 2011-2012; Solé Prillaman 2013; Stephen Pettigrew 2013-2014; Anton Strezhnev 2014-2015; Mayya Komisarchik 2015-2016; Connor Jerzak 2016

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## Schedule

Wednesday, August 17, 2016

9:00 - 9:30, Room K354<sup>1</sup>, Breakfast.

9:30 - 11:30, K354, Introduction and lecture: Notation and functions (Mayya)

11:30 - 12:00, K354, Setting up computing software.

*Please bring your laptops every day.*

12:00 - 1:00, K354, Lunch provided in K354.

1:00 - 4:00, K354 Intro to R and  $\LaTeX$

Thursday, August 18, 2016

9:00 - 9:30, K354, Breakfast.

9:30 - 12:00, RK354, Lecture: Linear algebra (Connor)

12:00 - 1:00, K354, Lunch with Prof. Matt Blackwell.

1:00 - 4:00, K354 or CGIS Computer Lab, R Computing/Practice problems

Students will switch at 2:30.

Friday, August 19, 2016

9:00 - 9:30, K354, Breakfast.

9:30 - 12:00, K354, Lecture: Calculus I (Mayya)

12:00 - 1:00, Lunch with Prof. Xiang Zhou.

1:00 - 4:00, K354 or CGIS Computer Lab, R Computing/Practice problems

Students will switch at 2:30.

Monday, August 22, 2016

9:00 - 9:30, K354, Breakfast.

9:30 - 12:00, K354, Lecture: Calculus II (Connor)

12:00 - 1:00, K354, Lunch with Prof. Ryan Enos.

1:00 - 4:00, K354 or CGIS Computer Lab, R Computing/Practice problems

Students will switch at 2:30.

Tuesday, August 23, 2016

9:00 - 9:30, K354, Breakfast.

9:30 - 12:00, K354, Lecture: Probability I (Mayya)

12:00 - 1:00, K354, Lunch on your own.

1:00 - 4:00, K354 or CGIS Computer Lab,  $\LaTeX$  Computing/Practice problems

Students will switch at 2:30.

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<sup>1</sup>This location refers to Room K354 in CGIS Knafel, 1737 Cambridge St.

Wednesday, August 24, 2016

9:00 - 9:30, K354, Breakfast.

9:30 - 12:00, K354, Lecture: Probability II (Connor)

12:00 - 1:00, K354, Lunch on your own.

1:00 - 4:00, K354 or CGIS Computer Lab, R Computing/Practice problems

Students will switch at 2:30.

Thursday, August 25, 2016

No Prefresher (GSAS orientation and DudleyFest)

**Math (P)refresher for Political Scientists****Wednesday, August 17 - Wednesday, August 24, 2016****Breakfast 9am - 9:30am****Lecture 9:30am - 12:00pm****Section 1:00pm - 4:00pm****Mayya Komisarchik** (Instructor)  
mkomisarchik@fas.harvard.edu**Connor Jerzak** (Instructor)  
cjerzak@g.harvard.edu**Gary King** (Faculty Adviser)  
king@harvard.edu**Course Website**  
projects.iq.harvard.edu/prefresher

**PURPOSE:** Not only do the quantitative and formal modeling courses at Harvard require mathematics and computer programming — it’s becoming increasingly difficult to take courses in political economy, American politics, comparative politics, or international relations without encountering game-theoretic models or statistical analyses. One need only flip through the latest issues of the top political science journals to see that mathematics have entered the mainstream of political science. Even political philosophy has been influenced by mathematical thinking. Unfortunately, most undergraduate political science programs have not kept up with this trend — and first-year graduate students often find themselves lacking in basic technical skills. This course is not intended to be an introduction to game theory or quantitative methods. Rather, it introduces basic mathematics and computer skills needed for quantitative and formal modeling courses offered at Harvard.

**PREREQUISITES:** None. Students for whom the topics in this syllabus are completely foreign should not be scared off. They have the perfect background for this course — the ones in most need of a “prefresh”ing before they take further courses with technical content. Students who have previously had some of this material, but have not used it in a while, should take this course to “refresh” their knowledge of the topics.

**STRUCTURE & REQUIREMENTS:** The class will meet twice a day, 9:00am – 12:00pm and 1:00pm – 4:00pm. This course is not for credit and has no exams. No one but the student will know how well he or she did. However, it still requires a significant commitment from students. Lectures will focus on major mathematical topics that are used in statistical and formal modeling in political science. Sections will be divided into two parts. During problem-solving sections, students are given exercises to work on (or as homework if not finished then) and students are encouraged to work on the exercises in groups of two or three. You learn more quickly when everyone else is working on the same problems! During computing sections, we will introduce you to the computing environment and software packages that are used in the departmental methods sequence. Math isn’t a spectator sport — you have to do it to learn it.

**COMPUTING:** All of the methods courses in the department, and increasingly courses in formal theory as well, make extensive use of the computational resources available at Harvard. Students will be introduced to  $\text{\LaTeX}$  (a typesetting language useful for producing documents with mathematical content) and R (the statistical computing language/environment used in the department’s method courses). These resources are very powerful, but have something of a steep learning curve; one of the goals of the prefresher is to give students a head start on these programs.

**TEXTBOOKS:** The text for this course is the textbook by Jeff Gill. In previous years we’ve required students to purchase this book. This year we don’t have such a requirement, although you are welcome to acquire it if you would like an additional reference.

Gill, Jeff. 2006. *Essential Mathematics for Political and Social Research*. Cambridge, England: Cambridge University Press.

There are several other recommended texts that you may wish to consult during the course. In particular, Simon and Blume is useful for those who will be taking formal modeling courses in the Government or Economics departments.

Simon, Carl P. and Lawrence Blume. 1994. *Mathematics for Economists*. New York: Norton.

Wackerly, Dennis, William Mendenhall, and Richard Scheaffer. 1996. *Mathematical Statistics with Applications*, 5th edition.

Hahn, Harley. 1996. *Harley Hahn's Student Guide to Unix*, 2nd edition.

## Lecture Schedule:

**Wednesday, August 17; CGIS Knafel K354****Lecture 1: Notation and Functions****R tutorial 1: Basics of R****L<sup>A</sup>T<sub>E</sub>X tutorial 1**

**Topics:** Dimensionality. Interval Notation for  $\mathbf{R}^1$ .  
 Neighborhoods: Intervals, Disks, and Balls.  
 Sets, Sets, and More Sets. Introduction to Functions.  
 Domain and Range. Some General Types of Functions.  
 Log, Ln, and  $e$ . Other Useful Functions. Graphing Functions.  
 Solving for Variables. Finding Roots. Limit of a Function.  
 Continuity.

**Recommended Reading:** Gill Ch. 1, 5.2; SB 2.1-2, 12.3-5, 10.1, 13.1-2, 5.1-4

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**Thursday, August 18; CGIS Knafel K354****Lecture 2: Linear Algebra****R tutorial 2: Working with data in R**

**Topics:** Working with Vectors. Linear Independence.  
 Basics of Matrix Algebra. Square Matrices.  
 Linear Equations. Systems of Linear Equations.  
 Systems of Equations as Matrices. Solving  
 Augmented Matrices and Systems of Equations.  
 Rank. The Inverse of a Matrix. Inverse of Larger Matrices.

**Recommended Reading:** Gill Ch. 3 & 4; SB 6.1, 7.1-4, 8.1-4, 9.1-2, 10.1-4, 11.1,

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**Friday, August 19; CGIS Knafel K354****Lecture 3: Calculus I****R tutorial 3: Logical statements and for loops**

**Topics:** Sequences. Limit of a Sequence. Series. Derivatives.  
 Higher-Order Derivatives. Composite Functions and the  
 Chain Rule. Derivatives of Exp and Ln. Maxima and Minima.  
 Partial Derivatives. L'Hôpital's Rule.  
 Derivative Calculus in 6 Steps.

**Recommended Reading:** Gill Ch. 5.3-4, 6.4; SB 12.1-2, 2.3-6, 3.1-2, 3.5, 4.1-2, 5.5

## Monday, August 22; CGIS Knafel K354

### Lecture 4: Calculus II

#### R tutorial 4: Loops, apply, and other functions

**Topics:** The Indefinite Integral: The Antiderivative.  
Common Rules of Integration. The Definite  
Integral: The Area under the Curve.  
Integration by Substitution. Integration by Parts.

**Recommended Reading:** Gill Ch. 6.2-3, 5.5-6; SB 14.1, 14.3-4, Appendix 4.1-3

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## Tuesday, August 23; CGIS Knafel K354

### Lecture 6: Probability I

#### L<sup>A</sup>T<sub>E</sub>X tutorial 2

**Topics:** Counting. Sets. Probability.  
Conditional Probability and Bayes' Rule.  
Independence.

**Recommended Reading:** Gill Ch. 7; WMS 2.1-11

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## Wednesday, August 24; CGIS Knafel K354

### Lecture 7: Probability II

#### R tutorial 6: Managing data in R and debugging code

**Topics:** Levels of Measurement. Random Variables.  
Discrete Distributions. Continuous Distributions.  
Expectation. Special Discrete Distributions.  
Special Continuous Distributions. Joint Distributions.  
Summarizing Observed Data.

**Recommended Reading:** Gill Ch. 8; WMS 3.1-4, 3.8, 4.1-5, 4.8

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**Thursday, August 25**

**No PreFresher (GSAS orientation and DudleyFest)**

# 1 Math Notes

## 1.1 Functions and Notation

### Today's Topics :

Dimensionality; Interval Notation for  $\mathbf{R}^1$ ; Neighborhoods: Intervals, Disks, and Balls; Introduction to Functions; Domain and Range; Some General Types of Functions; Log, Ln, and e; Other Useful Functions; Graphing Functions; Solving for Variables; Finding Roots; Limit of a Function; Continuity; Sets, Sets, and More Sets;

### 1.1.1 Dimensionality

- $\mathbf{R}^1$  is the set of all **real** numbers extending from  $-\infty$  to  $+\infty$  — i.e., the real number line.
- $\mathbf{R}^n$  is an  $n$ -dimensional space (often referred to as Euclidean space), where each of the  $n$  axes extends from  $-\infty$  to  $+\infty$ .

Examples:

1.  $\mathbf{R}^1$  is a one dimensional line.
2.  $\mathbf{R}^2$  is a two dimensional plane.
3.  $\mathbf{R}^3$  is a three dimensional space.
4.  $\mathbf{R}^4$  could be 3-D plus time (or temperature, etc).

Points in  $\mathbf{R}^n$  are ordered  $n$ -tuples, where each element of the  $n$ -tuple represents the coordinate along that dimension.

$\mathbf{R}^1$ : (3)

$\mathbf{R}^2$ : (-15, 5)

$\mathbf{R}^3$ : (86, 4, 0)

### 1.1.2 Interval Notation for $\mathbf{R}^1$

- **Open interval:**  $(a, b) \equiv \{x \in \mathbf{R}^1 : a < x < b\}$

$x$  is a one-dimensional element in which  $x$  is greater than  $a$  and less than  $b$

- **Closed interval:**  $[a, b] \equiv \{x \in \mathbf{R}^1 : a \leq x \leq b\}$

$x$  is a one-dimensional element in which  $x$  is greater or equal to than  $a$  and less than or equal to  $b$

- **Half open, half closed:**  $(a, b] \equiv \{x \in \mathbf{R}^1 : a < x \leq b\}$

$x$  is a one-dimensional element in which  $x$  is greater than  $a$  and less than or equal to  $b$

### 1.1.3 Neighborhoods: Intervals, Disks, and Balls

- In many areas of math, we need a formal construct for what it means to be “near” a point  $\mathbf{c}$  in  $\mathbf{R}^n$ . This is generally called the **neighborhood** of  $\mathbf{c}$ . It’s represented by an open interval, disk, or ball, depending on whether  $\mathbf{R}^n$  is of one, two, or more dimensions, respectively. Given the point  $c$ , these are defined as

1.  $\epsilon$ -**interval** in  $\mathbf{R}^1$ :  $\{x : |x - c| < \epsilon\}$   
 $x$  is in the neighborhood of  $\mathbf{c}$  if it is in the open interval  $(c - \epsilon, c + \epsilon)$ .
2.  $\epsilon$ -**disk** in  $\mathbf{R}^2$ :  $\{x : \|x - c\| < \epsilon\}$   
 $x$  is in the neighborhood of  $\mathbf{c}$  if it is inside the circle or disc with center  $\mathbf{c}$  and radius  $\epsilon$ .
3.  $\epsilon$ -**ball** in  $\mathbf{R}^n$ :  $\{x : \|x - c\| < \epsilon\}$   
 $x$  is in the neighborhood of  $\mathbf{c}$  if it is inside the sphere or ball with center  $\mathbf{c}$  and radius  $\epsilon$ .

### 1.1.4 Introduction to Functions

- A **function** (in  $\mathbf{R}^1$ ) is a mapping, or transformation, that relates members of one set to members of another set. For instance, if you have two sets: set  $A$  and set  $B$ , a function from  $A$  to  $B$  maps every value  $a$  in set  $A$  such that  $f(a) \in B$ . Functions can be “many-to-one”, where many values or combinations of values from set  $A$  produce a single output in set  $B$ , or they can be “one-to-one”, where each value in set  $A$  corresponds to a single value in set  $B$ .

Examples: Mapping notation

1. Function of one variable:  $f : \mathbf{R}^1 \rightarrow \mathbf{R}^1$   
 $f(x) = x + 1$   
 For each  $x$  in  $\mathbf{R}^1$ ,  $f(x)$  assigns the number  $x + 1$ .
2. Function of two variables:  $f : \mathbf{R}^2 \rightarrow \mathbf{R}^1$   
 $f(x, y) = x^2 + y^2$   
 For each ordered pair  $(x, y)$  in  $\mathbf{R}^2$ ,  $f(x, y)$  assigns the number  $x^2 + y^2$ .

We often use one variable  $x$  as input and another  $y$  as output.

Example:  $y = x + 1$

- Input variable also called **independent** or **explanatory** variable. Output variable also called **dependent** or **response** variable.

### 1.1.5 Domain and Range/Image

Some functions are defined only on proper subsets of  $\mathbf{R}^n$ .

- **Domain**: the set of numbers in  $X$  at which  $f(x)$  is defined.
- **Range**: elements of  $Y$  assigned by  $f(x)$  to elements of  $X$ , or

$$f(X) = \{y : y = f(x), x \in X\}$$

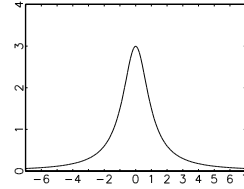
Most often used when talking about a function  $f : \mathbf{R}^1 \rightarrow \mathbf{R}^1$ .

- **Image:** same as range, but more often used when talking about a function  $f : \mathbf{R}^n \rightarrow \mathbf{R}^1$ .

Examples:

$$f(x) = \frac{3}{1+x^2}$$

1. Domain:  
Range:

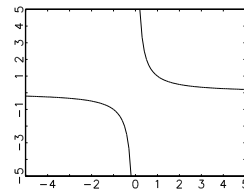


$$2. f(x) = \begin{cases} x + 1, & 1 \leq x \leq 2 \\ 0, & x = 0 \\ 1 - x, & -2 \leq x \leq -1 \end{cases}$$

- Domain:  
Range:

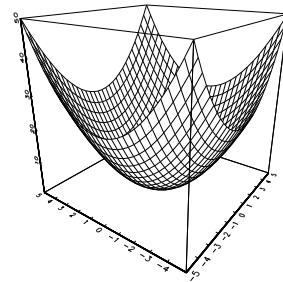
$$f(x) = 1/x$$

3. Domain:  
Range:



$$f(x, y) = x^2 + y^2$$

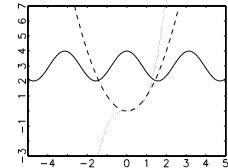
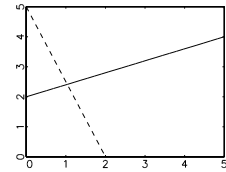
4. Domain  
Range:



### 1.1.6 Some General Types of Functions

- **Monomials:**  $f(x) = ax^k$   
 $a$  is the coefficient.  $k$  is the degree.  
Examples:  $y = x^2$ ,  $y = -\frac{1}{2}x^3$
- **Polynomials:** sum of monomials.  
Examples:  $y = -\frac{1}{2}x^3 + x^2$ ,  $y = 3x + 5$   
The degree of a polynomial is the highest degree of its monomial terms. Also, it's often a good idea to write polynomials with terms in decreasing degree.
- **Rational Functions:** ratio of two polynomials.  
Examples:  $y = \frac{x}{2}$ ,  $y = \frac{x^2+1}{x^2-2x+1}$

- **Exponential Functions:** Example:  $y = 2^x$
- **Trigonometric Functions:** Examples:  $y = \cos(x)$ ,  $y = 3 \sin(4x)$
- **Linear:** polynomial of degree 1.  
Example:  $y = mx + b$ , where  $m$  is the slope and  $b$  is the  $y$ -intercept.
- **Nonlinear:** anything that isn't constant or polynomial of degree 1.  
Examples:  $y = x^2 + 2x + 1$ ,  $y = \sin(x)$ ,  $y = \ln(x)$ ,  $y = e^x$



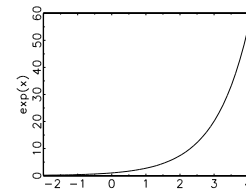
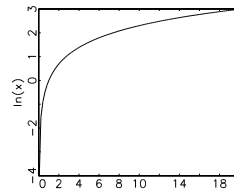
### 1.1.7 Log, Ln, and $e$

- **Relationship of logarithmic and exponential functions:**

$$y = \log_a(x) \iff a^y = x$$

The log function can be thought of as an inverse for exponential functions.  $a$  is referred to as the “base” of the logarithm.

- **Common Bases:** The two most common logarithms are base 10 and base  $e$ .
  1. Base 10:  $y = \log_{10}(x) \iff 10^y = x$   
Except in the field of statistics, the base 10 logarithm is often simply written as “ $\log(x)$ ” with no base denoted.
  2. Base  $e$ :  $y = \log_e(x) \iff e^y = x$   
The base  $e$  logarithm is referred to as the “natural” logarithm and is written as “ $\ln(x)$ ”, or as “ $\log(x)$ ” in the field of statistics.



- Properties of exponential functions:

1.  $a^x a^y = a^{x+y}$
2.  $a^{-x} = 1/a^x$
3.  $a^x / a^y = a^{x-y}$
4.  $(a^x)^y = a^{xy}$
5.  $a^0 = 1$

- Properties of logarithmic functions (any base):

Generally, when statisticians or social scientists write  $\log(x)$  they mean  $\log_e(x)$ . In other words:  $\log_e(x) \equiv \ln(x) \equiv \log(x)$

$$\log_a(a^x) = x \text{ and } a^{\log_a(x)} = x$$

1.  $\log(xy) = \log(x) + \log(y)$
2.  $\log(x^y) = y \log(x)$
3.  $\log(1/x) = \log(x^{-1}) = -\log(x)$
4.  $\log(x/y) = \log(x \cdot y^{-1}) = \log(x) + \log(y^{-1}) = \log(x) - \log(y)$
5.  $\log(1) = \log(e^0) = 0$

- **Change of Base Formula:** Use the change of base formula to switch bases as necessary:

$$\log_b(x) = \frac{\log_a(x)}{\log_a(b)}$$

Example:

$$\log_{10}(x) = \frac{\ln(x)}{\ln(10)}$$

Examples:

1.  $\log_{10}(\sqrt{10}) =$
2.  $\log_{10}(1) =$
3.  $\log_{10}(10) =$
4.  $\log_{10}(100) =$
5.  $\ln(1) = \ln(e^0) =$
6.  $\ln(e) =$

### 1.1.8 Other Useful Functions

- **Factorials!:**

$$x! = x \cdot (x - 1) \cdot (x - 2) \cdots (1)$$

- **Modulo:**

This function calculates the remainder when you divide one number by another, and can be extremely useful for programming.

$x \bmod y$  or  $x \% y$

Examples:  $17 \bmod 3 = 2$        $100 \% 30 = 10$

- **Summation:**

$$\sum_{i=1}^n x_i = x_1 + x_2 + x_3 + \cdots + x_n$$

Properties:

1.  $\sum_{i=1}^n cx_i = c \sum_{i=1}^n x_i$
2.  $\sum_{i=1}^n (x_i + y_i) = \sum_{i=1}^n x_i + \sum_{i=1}^n y_i$
3.  $\sum_{i=1}^n c = nc$

- **Product:**

$$\prod_{i=1}^n x_i = x_1 x_2 x_3 \cdots x_n$$

Properties:

1.  $\prod_{i=1}^n cx_i = c^n \prod_{i=1}^n x_i$
2.  $\prod_{i=1}^n (x_i + y_i) =$  a total mess
3.  $\prod_{i=1}^n c = c^n$

You can use logs to go between sum and product notation. This will be particularly important when you're learning maximum likelihood estimation.

$$\begin{aligned} \log\left(\prod_{i=1}^n x_i\right) &= \log(x_1 \cdot x_2 \cdot x_3 \cdots x_n) \\ &= \log(x_1) + \log(x_2) + \log(x_3) + \cdots + \log(x_n) \\ &= \sum_{i=1}^n \log(x_i) \end{aligned}$$

Therefore, you can see that the log of a product is equal to the sum of the logs. We can write this more generally by adding in a constant,  $c$ :

$$\begin{aligned} \log\left(\prod_{i=1}^n cx_i\right) &= \log(cx_1 \cdot cx_2 \cdots cx_n) \\ &= \log(c^n \cdot x_1 \cdot x_2 \cdots x_n) \\ &= \log(c^n) + \log(x_1) + \log(x_2) + \cdots + \log(x_n) \\ &= n \log(c) + \sum_{i=1}^n \log(x_i) \end{aligned}$$

### 1.1.9 Graphing Functions

What can a graph tell you about a function?

1. Is the function increasing or decreasing? Over what part of the domain?
2. How “fast” does it increase or decrease?
3. Are there global or local maxima and minima? Where?
4. Are there inflection points?
5. Is the function continuous?
6. Is the function differentiable?
7. Does the function tend to some limit?
8. Other questions related to the substance of the problem at hand.

### 1.1.10 Solving for Variables and Finding Inverses

Sometimes we’re given a function  $y = f(x)$  and we want to find how  $x$  varies as a function of  $y$ .

If  $f$  is a one-to-one mapping, then it has an inverse.

Use algebra to move  $x$  to the left hand side (LHS) of the equation and so that the right hand side (RHS) is only a function of  $y$ .

Examples: (we want to solve for  $x$ )

1.  $y = 3x + 2 \implies -3x = 2 - y \implies 3x = y - 2 \implies x = \frac{1}{3}(y - 2)$
2.  $y = 3x - 4z + 2 \implies y + 4z - 2 = 3x \implies x = \frac{1}{3}(y + 4z - 2)$
3.  $y = e^x + 4 \implies y - 4 = e^x \implies \ln(y - 4) = \ln(e^x) \implies x = \ln(y - 4)$

Often, the inverse does not exist, or is ill-defined.

Example: We’re given the function  $y = x^2$  (a parabola). Solving for  $x$ , we get  $x = \pm\sqrt{y}$ . For each value of  $y$ , there are two values of  $x$ .

### 1.1.11 Finding the Roots or Zeroes of a Function

Solving for variables is especially important when we want to find the **roots** of an equation: those values of variables that cause an equation to equal zero.

Especially important in finding equilibria and in doing maximum likelihood estimation.

- **Procedure:** Given  $y = f(x)$ , set  $f(x) = 0$ . Solve for  $x$ .

- **Multiple Roots:**

$$f(x) = x^2 - 9 \implies 0 = x^2 - 9 \implies 9 = x^2 \implies \pm\sqrt{9} = \sqrt{x^2} \implies \pm 3 = x$$

- **Quadratic Formula:** For quadratic equations  $ax^2 + bx + c = 0$ , use the quadratic formula:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Examples:

1.  $f(x) = 3x + 2$
2.  $f(x) = e^{-x} - 10$
3.  $f(x) = x^2 + 3x - 4 = 0$

### 1.1.12 The Limit of a Function

We're often interested in determining if a function  $f$  approaches some number  $L$  as its independent variable  $x$  moves to some number  $c$  (usually 0 or  $\pm\infty$ ). If it does, we say that the limit of  $f(x)$ , as  $x$  approaches  $c$ , is  $L$ :  $\lim_{x \rightarrow c} f(x) = L$ .

For a limit  $L$  to exist, the function  $f(x)$  must approach  $L$  from both the left and right.

- **Limit of a function.** Let  $f(x)$  be defined at each point in some open interval containing the point  $c$ . Then  $L$  equals  $\lim_{x \rightarrow c} f(x)$  if for any (small positive) number  $\epsilon$ , there exists a corresponding number  $\delta > 0$  such that if  $0 < |x - c| < \delta$ , then  $|f(x) - L| < \epsilon$ .

Note:  $f(x)$  does not necessarily have to be defined at  $c$  for  $\lim_{x \rightarrow c}$  to exist.

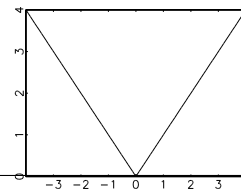
- **Uniqueness:**  $\lim_{x \rightarrow c} f(x) = L$  and  $\lim_{x \rightarrow c} f(x) = M \implies L = M$
- **Properties:** Let  $f$  and  $g$  be functions with  $\lim_{x \rightarrow c} f(x) = A$  and  $\lim_{x \rightarrow c} g(x) = B$ .

1.  $\lim_{x \rightarrow c} [f(x) + g(x)] = \lim_{x \rightarrow c} f(x) + \lim_{x \rightarrow c} g(x)$
2.  $\lim_{x \rightarrow c} \alpha f(x) = \alpha \lim_{x \rightarrow c} f(x)$
3.  $\lim_{x \rightarrow c} f(x)g(x) = [\lim_{x \rightarrow c} f(x)][\lim_{x \rightarrow c} g(x)]$
4.  $\lim_{x \rightarrow c} \frac{f(x)}{g(x)} = \frac{\lim_{x \rightarrow c} f(x)}{\lim_{x \rightarrow c} g(x)}$ , provided  $\lim_{x \rightarrow c} g(x) \neq 0$

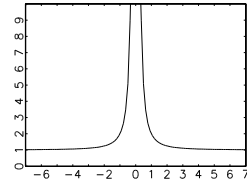
Note: In a couple days we'll talk about L'Hôpital's Rule, which uses simple calculus to help find the limits of functions like this.

Examples:

1.  $\lim_{x \rightarrow c} k =$
2.  $\lim_{x \rightarrow c} x =$
3.  $\lim_{x \rightarrow 0} |x| =$



$$4. \lim_{x \rightarrow 0} \left(1 + \frac{1}{x^2}\right) =$$



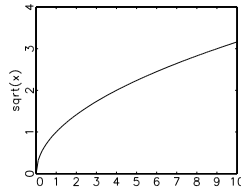
$$5. \lim_{x \rightarrow 2} (2x - 3) =$$

$$6. \lim_{x \rightarrow c} x^n =$$

• **Types of limits:**

1. **Right-hand limit:** The value approached by  $f(x)$  when you move from right to left.

Example:  $\lim_{x \rightarrow 0^+} \sqrt{x} = 0$



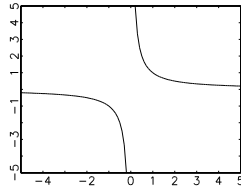
2. **Left-hand limit:** The value approached by  $f(x)$  when you move from left to right.

3. **Infinity:** The value approached by  $f(x)$  as  $x$  grows infinitely large. Sometimes this may be a number; sometimes it might be  $\infty$  or  $-\infty$ .

4. **Negative infinity:** The value approached by  $f(x)$  as  $x$  grows infinitely negative. Sometimes this may be a number; sometimes it might be  $\infty$  or  $-\infty$ .

Example:  $\lim_{x \rightarrow \infty} 1/x = 0$

$\lim_{x \rightarrow -\infty} 1/x = 0$

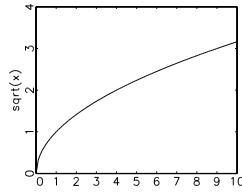


### 1.1.13 Continuity

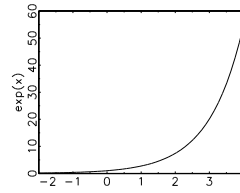
- **Continuity:** Suppose that the domain of the function  $f$  includes an open interval containing the point  $c$ . Then  $f$  is continuous at  $c$  if  $\lim_{x \rightarrow c} f(x)$  exists and if  $\lim_{x \rightarrow c} f(x) = f(c)$ . Further,  $f$  is continuous on an open interval  $(a, b)$  if it is continuous at each point in the interval.

Examples: Continuous functions.

$$f(x) = \sqrt{x}$$

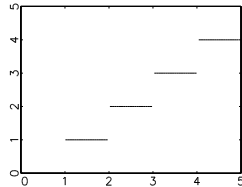


$$f(x) = e^x$$

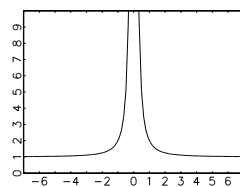


Examples: Discontinuous functions.

$$f(x) = \text{floor}(x)$$



$$f(x) = 1 + \frac{1}{x^2}$$



- Properties:

1. If  $f$  and  $g$  are continuous at point  $c$ , then  $f + g$ ,  $f - g$ ,  $f \cdot g$ ,  $|f|$ , and  $\alpha f$  are continuous at point  $c$  also.  $f/g$  is continuous, provided  $g(c) \neq 0$ .
2. **Boundedness:** If  $f$  is continuous on the closed bounded interval  $[a, b]$ , then there is a number  $K$  such that  $|f(x)| \leq K$  for each  $x$  in  $[a, b]$ .
3. **Max/Min:** If  $f$  is continuous on the closed bounded interval  $[a, b]$ , then  $f$  has a maximum and a minimum on  $[a, b]$ . They may be located at the end points.

### 1.1.14 Sets, Sets, and More Sets

- **Interior Point:** The point  $\mathbf{x}$  is an interior point of the set  $S$  if  $\mathbf{x}$  is in  $S$  and if there is some  $\epsilon$ -ball around  $\mathbf{x}$  that contains only points in  $S$ . The **interior** of  $S$  is the collection of all interior points in  $S$ . The interior can also be defined as the union of all open sets in  $S$ . If the set  $S$  is circular, the interior points are everything inside of the circle, but not on the circle's rim.  
Example: The interior of the set  $\{(x, y) : x^2 + y^2 \leq 4\}$  is  $\{(x, y) : x^2 + y^2 < 4\}$ .
- **Boundary Point:** The point  $\mathbf{x}$  is a boundary point of the set  $S$  if every  $\epsilon$ -ball around  $\mathbf{x}$  contains both points that are in  $S$  and points that are outside  $S$ . The **boundary** is the collection of all boundary points.  
If the set  $S$  is circular, the boundary points are everything on the circle's rim.  
Example: The boundary of  $\{(x, y) : x^2 + y^2 \leq 4\}$  is  $\{(x, y) : x^2 + y^2 = 4\}$ .
- **Open:** A set  $S$  is open if for each point  $\mathbf{x}$  in  $S$ , there exists an open  $\epsilon$ -ball around  $\mathbf{x}$  completely contained in  $S$ .  
If the set  $S$  is circular and open, the points contained within the set get infinitely close to the circle's rim, but do not touch it.  
Example:  $\{(x, y) : x^2 + y^2 < 4\}$
- **Closed:** A set  $S$  is closed if it contains all of its boundary points.  
If the set  $S$  is circular and closed, the set contains all points within the rim as well as the rim itself.  
Example:  $\{(x, y) : x^2 + y^2 \leq 4\}$

Note: a set may be neither open nor closed.

Example:  $\{(x, y) : 2 < x^2 + y^2 \leq 4\}$

- **Complement:** The complement of set  $S$  is everything outside of  $S$ .  
If the set  $S$  is circular, the complement of  $S$  is everything outside of the circle.  
Example: The complement of  $\{(x, y) : x^2 + y^2 \leq 4\}$  is  $\{(x, y) : x^2 + y^2 > 4\}$ .
- **Closure:** The closure of set  $S$  is the smallest closed set that contains  $S$ .  
Example: The closure of  $\{(x, y) : x^2 + y^2 < 4\}$  is  $\{(x, y) : x^2 + y^2 \leq 4\}$
- **Bounded:** A set  $S$  is bounded if it can be contained within an  $\epsilon$ -ball.  
Examples: Bounded: any interval that doesn't have  $\infty$  or  $-\infty$  as endpoints; any disk in a plane with finite radius.  
Unbounded: the set of integers in  $\mathbf{R}^1$ ; any ray.
- **Compact:** A set is compact if and only if it is both closed and bounded.
- **Empty:** The empty (or null) set is a unique set that has no elements, denoted by  $\{\}$  or  $\emptyset$ .<sup>3</sup>  
Examples: The set of squares with 5 sides; the set of countries south of the South Pole.

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<sup>3</sup>The set,  $S$ , denoted by  $\{\emptyset\}$  is technically *not* empty. That is because this set contains the empty set within it, so  $S$  is not empty.

## 1.2 Linear Algebra

### Today's Topics:

Working with Vectors ; Linear Independence; Basics of Matrix Algebra; Square Matrices; Linear Equations; Systems of Linear Equations; Systems of Equations as Matrices; Solving Augmented Matrices and Systems of Equations; Rank; The Inverse of a Matrix; Inverse of Larger Matrices

### 1.2.1 Working with Vectors

- **Vector:** A vector in  $n$ -space is an ordered list of  $n$  numbers. These numbers can be represented as either a row vector or a column vector:

$$\mathbf{v} (v_1 \ v_2 \ \dots \ v_n), \quad \mathbf{v} = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix}$$

We can also think of a vector as defining a point in  $n$ -dimensional space, usually  $\mathbf{R}^n$ ; each element of the vector defines the coordinate of the point in a particular direction.

- **Vector Addition and Subtraction:** If two vectors,  $\mathbf{u}$  and  $\mathbf{v}$ , have the same length (i.e. have the same number of elements), they can be added (subtracted) together:

$$\mathbf{u} + \mathbf{v} = (u_1 + v_1 \ u_2 + v_2 \ \dots \ u_k + v_n)$$

$$\mathbf{u} - \mathbf{v} = (u_1 - v_1 \ u_2 - v_2 \ \dots \ u_k - v_n)$$

- **Scalar Multiplication:** The product of a scalar  $c$  (i.e. a constant) and vector  $\mathbf{v}$  is:

$$c\mathbf{v} = (cv_1 \ cv_2 \ \dots \ cv_n)$$

- **Vector Inner Product:** The inner product (also called the dot product or scalar product) of two vectors  $\mathbf{u}$  and  $\mathbf{v}$  is again defined iff they have the same number of elements

$$\mathbf{u} \cdot \mathbf{v} = u_1v_1 + u_2v_2 + \dots + u_nv_n = \sum_{i=1}^n u_iv_i$$

If  $\mathbf{u} \cdot \mathbf{v} = 0$ , the two vectors are orthogonal (or perpendicular).

- **Vector Norm:** The norm of a vector is a measure of its length. There are many different ways to calculate the norm, but the most common of is the Euclidean norm (which corresponds to our usual conception of distance in three-dimensional space):

$$\|\mathbf{v}\| = \sqrt{\mathbf{v} \cdot \mathbf{v}} = \sqrt{v_1v_1 + v_2v_2 + \dots + v_nv_n}$$

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Much of the material and examples for this lecture are taken from Gill (2006) *Essential Mathematics for Political and Social Scientists*, Simon & Blume (1994) *Mathematics for Economists* and Kolman (1993) *Introductory Linear Algebra with Applications*.

### 1.2.2 Linear Independence

- **Linear combinations:** The vector  $\mathbf{u}$  is a linear combination of the vectors  $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k$  if

$$\mathbf{u} = c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \dots + c_k\mathbf{v}_k$$

- **Linear independence:** A set of vectors  $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k$  is linearly independent if the only solution to the equation

$$c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \dots + c_k\mathbf{v}_k = \mathbf{0}$$

is  $c_1 = c_2 = \dots = c_k = 0$ . If another solution exists, the set of vectors is linearly dependent.

A set  $S$  of vectors is linearly dependent iff at least one of the vectors in  $S$  can be written as a linear combination of the other vectors in  $S$ .

Linear independence is only defined for sets of vectors with the same number of elements; any linearly independent set of vectors in  $n$ -space contains at most  $n$  vectors.

Examples: Are the following sets of vectors linearly independent?

1.

$$\mathbf{v}_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \mathbf{v}_2 = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}, \mathbf{v}_3 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

2.

$$\mathbf{v}_1 = \begin{pmatrix} 3 \\ 2 \\ -1 \end{pmatrix}, \mathbf{v}_2 = \begin{pmatrix} -2 \\ 2 \\ 4 \end{pmatrix}, \mathbf{v}_3 = \begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix}$$

### 1.2.3 Basics of Matrix Algebra

- **Matrix:** A matrix is an array of real numbers arranged in  $m$  rows by  $n$  columns. The dimensionality of the matrix is defined as the number of rows by the number of columns,  $m \times n$ .

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{pmatrix}$$

Note that you can think of vectors as special cases of matrices; a column vector of length  $k$  is a  $k \times 1$  matrix, while a row vector of the same length is a  $1 \times k$  matrix.

It's also useful to think of matrices as being made up of a collection of row or column vectors. For example,

$$\mathbf{A} = (\mathbf{a}_1 \quad \mathbf{a}_2 \quad \dots \quad \mathbf{a}_m)$$

- **Matrix Addition:** Let  $\mathbf{A}$  and  $\mathbf{B}$  be two  $m \times n$  matrices.

$$\mathbf{A} + \mathbf{B} = \begin{pmatrix} a_{11} + b_{11} & a_{12} + b_{12} & \cdots & a_{1n} + b_{1n} \\ a_{21} + b_{21} & a_{22} + b_{22} & \cdots & a_{2n} + b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} + b_{m1} & a_{m2} + b_{m2} & \cdots & a_{mn} + b_{mn} \end{pmatrix}$$

Note that matrices  $\mathbf{A}$  and  $\mathbf{B}$  must have the same dimensionality, in which case they are **conformable for addition**.

Example:

$$\mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 1 & 2 & 1 \\ 2 & 1 & 2 \end{pmatrix}$$

$$\mathbf{A} + \mathbf{B} =$$

- **Scalar Multiplication:** Given the scalar  $s$ , the scalar multiplication of  $s\mathbf{A}$  is

$$s\mathbf{A} = s \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} = \begin{pmatrix} sa_{11} & sa_{12} & \cdots & sa_{1n} \\ sa_{21} & sa_{22} & \cdots & sa_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ sa_{m1} & sa_{m2} & \cdots & sa_{mn} \end{pmatrix}$$

Example:

$$s = 2, \quad \mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$$

$$s\mathbf{A} =$$

- **Matrix Multiplication:** If  $\mathbf{A}$  is an  $m \times k$  matrix and  $\mathbf{B}$  is a  $k \times n$  matrix, then their product  $\mathbf{C} = \mathbf{AB}$  is the  $m \times n$  matrix where

$$c_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{ik}b_{kj}$$

Examples:

$$1. \begin{pmatrix} a & b \\ c & d \\ e & f \end{pmatrix} \begin{pmatrix} A & B \\ C & D \end{pmatrix} =$$

$$2. \begin{pmatrix} 1 & 2 & -1 \\ 3 & 1 & 4 \end{pmatrix} \begin{pmatrix} -2 & 5 \\ 4 & -3 \\ 2 & 1 \end{pmatrix} =$$

Note that the number of columns of the first matrix must equal the number of rows of the second matrix, in which case they are **conformable for multiplication**. The sizes of the matrices (including the resulting product) must be

$$(m \times k)(k \times n) = (m \times n)$$

Also note that if  $\mathbf{AB}$  exists,  $\mathbf{BA}$  exists only if  $\dim(\mathbf{A}) = m \times n$  and  $\dim(\mathbf{B}) = n \times m$ . This does not mean that  $\mathbf{AB} = \mathbf{BA}$ .  $\mathbf{AB} = \mathbf{BA}$  is true *only* in special circumstances, like when  $\mathbf{A}$  or  $\mathbf{B}$  is an identity matrix,  $\mathbf{A} = \mathbf{B}^{-1}$ , or  $\mathbf{A} = \mathbf{B}$  and  $\mathbf{A}$  is idempotent.

- **Laws of Matrix Algebra:**

1. Associative:  $(\mathbf{A} + \mathbf{B}) + \mathbf{C} = \mathbf{A} + (\mathbf{B} + \mathbf{C})$   
 $(\mathbf{AB})\mathbf{C} = \mathbf{A}(\mathbf{BC})$
2. Commutative:  $\mathbf{A} + \mathbf{B} = \mathbf{B} + \mathbf{A}$
3. Distributive:  $\mathbf{A}(\mathbf{B} + \mathbf{C}) = \mathbf{AB} + \mathbf{AC}$   
 $(\mathbf{A} + \mathbf{B})\mathbf{C} = \mathbf{AC} + \mathbf{BC}$

Commutative law for multiplication does not hold: the order of multiplication matters:

$$\mathbf{AB} \neq \mathbf{BA}$$

Example:

$$\mathbf{A} = \begin{pmatrix} 1 & 2 \\ -1 & 3 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 2 & 1 \\ 0 & 1 \end{pmatrix}$$

$$\mathbf{AB} = \begin{pmatrix} 2 & 3 \\ -2 & 2 \end{pmatrix}, \quad \mathbf{BA} = \begin{pmatrix} 1 & 7 \\ -1 & 3 \end{pmatrix}$$

- **Transpose:** The transpose of the  $m \times n$  matrix  $\mathbf{A}$  is the  $n \times m$  matrix  $\mathbf{A}^T$  (also written  $\mathbf{A}'$ ) obtained by interchanging the rows and columns of  $\mathbf{A}$ .

Examples:

1.  $\mathbf{A} = \begin{pmatrix} 4 & -2 & 3 \\ 0 & 5 & -1 \end{pmatrix}, \quad \mathbf{A}^T = \begin{pmatrix} 4 & 0 \\ -2 & 5 \\ 3 & -1 \end{pmatrix}$
2.  $\mathbf{B} = \begin{pmatrix} 2 \\ -1 \\ 3 \end{pmatrix}, \quad \mathbf{B}^T = (2 \quad -1 \quad 3)$

- Properties of transposed matrices:

1.  $(\mathbf{A} + \mathbf{B})^T = \mathbf{A}^T + \mathbf{B}^T$
2.  $(\mathbf{A}^T)^T = \mathbf{A}$
3.  $(s\mathbf{A})^T = s\mathbf{A}^T$
4.  $(\mathbf{AB})^T = \mathbf{B}^T\mathbf{A}^T$

Example of  $(\mathbf{AB})^T = \mathbf{B}^T \mathbf{A}^T$ :

$$\mathbf{A} = \begin{pmatrix} 1 & 3 & 2 \\ 2 & -1 & 3 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 0 & 1 \\ 2 & 2 \\ 3 & -1 \end{pmatrix}$$

$$(\mathbf{AB})^T = \left[ \begin{pmatrix} 1 & 3 & 2 \\ 2 & -1 & 3 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 2 & 2 \\ 3 & -1 \end{pmatrix} \right]^T = \begin{pmatrix} 12 & 7 \\ 5 & -3 \end{pmatrix}$$

$$\mathbf{B}^T \mathbf{A}^T = \begin{pmatrix} 0 & 2 & 3 \\ 1 & 2 & -1 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ 3 & -1 \\ 2 & 3 \end{pmatrix} = \begin{pmatrix} 12 & 7 \\ 5 & -3 \end{pmatrix}$$

### 1.2.4 Square Matrices

- **Square** matrices have the same number of rows and columns; a  $k \times k$  square matrix is referred to as a matrix of order  $k$ .
- The **diagonal** of a square matrix is the vector of matrix elements that have the same subscripts. If  $\mathbf{A}$  is a square matrix of order  $k$ , then its diagonal is  $[a_{11}, a_{22}, \dots, a_{kk}]'$ .
- **Important Types of Square Matrices:**

1. **Identity Matrix:** The  $n \times n$  identity matrix  $\mathbf{I}_n$  is the matrix whose diagonal elements are 1 and all off-diagonal elements are 0. Examples:

$$\mathbf{I}_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \mathbf{I}_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

2. **Symmetric Matrix:** A matrix  $\mathbf{A}$  is symmetric if  $\mathbf{A} = \mathbf{A}'$ ; this implies that  $a_{ij} = a_{ji}$  for all  $i$  and  $j$ . Examples:

$$\mathbf{A} = \begin{pmatrix} 1 & 2 \\ 2 & 1 \end{pmatrix} = \mathbf{A}', \quad \mathbf{B} = \begin{pmatrix} 4 & 2 & -1 \\ 2 & 1 & 3 \\ -1 & 3 & 1 \end{pmatrix} = \mathbf{B}'$$

3. **Diagonal Matrix:** A matrix  $\mathbf{A}$  is diagonal if all of its non-diagonal entries are zero; formally, if  $a_{ij} = 0$  for all  $i \neq j$ . Examples:

$$\mathbf{A} = \begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 4 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4. **Triangular Matrix:** A matrix is triangular one of two cases. If all entries below the diagonal are zero ( $a_{ij} = 0$  for all  $i > j$ ), it is **upper triangular**. Conversely, if all entries above the diagonal are zero ( $a_{ij} = 0$  for all  $i < j$ ), it is **lower triangular**. Examples:

$$\mathbf{A}_{LT} = \begin{pmatrix} 1 & 0 & 0 \\ 4 & 2 & 0 \\ -3 & 2 & 5 \end{pmatrix}, \quad \mathbf{A}_{UT} = \begin{pmatrix} 1 & 7 & -4 \\ 0 & 3 & 9 \\ 0 & 0 & -3 \end{pmatrix}$$

### 1.2.5 Linear Equations

- **Linear Equation:**  $a_1x_1 + a_2x_2 + \cdots + a_nx_n = b$   
 $a_i$  are parameters or coefficients.  $x_i$  are variables or unknowns.

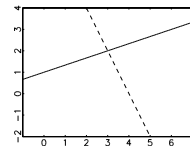
Linear because only one variable per term and degree is at most 1.

1.  $\mathbf{R}^2$ : line  $x_2 = \frac{b}{a_2} - \frac{a_1}{a_2}x_1$
2.  $\mathbf{R}^3$ : plane  $x_3 = \frac{b}{a_3} - \frac{a_1}{a_3}x_1 - \frac{a_2}{a_3}x_2$
3.  $\mathbf{R}^n$ : hyperplane

### 1.2.6 Systems of Linear Equations

Often we are interested in solving linear systems like

$$\begin{aligned}x - 3y &= -3 \\ 2x + y &= 8\end{aligned}$$



More generally, we might have a system of  $m$  equations in  $n$  unknowns

$$\begin{aligned}a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2 \\ \vdots & \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n &= b_m\end{aligned}$$

- A **solution** to a linear system of  $m$  equations in  $n$  unknowns is a set of  $n$  numbers  $x_1, x_2, \dots, x_n$  that satisfy each of the  $m$  equations.
  1.  $\mathbf{R}^2$ : intersection of the lines.
  2.  $\mathbf{R}^3$ : intersection of the planes.
  3.  $\mathbf{R}^n$ : intersection of the hyperplanes.

Example:  $x = 3$  and  $y = 2$  is the solution to the above  $2 \times 2$  linear system. Notice from the graph that the two lines intersect at  $(3, 2)$ .

Does a linear system have one, no, or multiple solutions?

For a system of 2 equations in 2 unknowns (i.e., two lines):

1. One solution: The lines intersect at exactly one point.
2. No solution: The lines are parallel.
3. Infinite solutions: The lines coincide.

- **Methods to solve linear systems:**

1. Substitution
2. Elimination of variables
3. Matrix methods

### 1.2.7 Systems of Equations as Matrices

Matrices provide an easy and efficient way to represent linear systems such as

$$\begin{array}{cccccc} a_{11}x_1 & + & a_{12}x_2 & + & \cdots & + & a_{1n}x_n & = & b_1 \\ a_{21}x_1 & + & a_{22}x_2 & + & \cdots & + & a_{2n}x_n & = & b_2 \\ \vdots & & & & & & & & \vdots \\ a_{m1}x_1 & + & a_{m2}x_2 & + & \cdots & + & a_{mn}x_n & = & b_m \end{array}$$

as

$$\mathbf{Ax} = \mathbf{b}$$

where

1. The  $m \times n$  **coefficient matrix**  $\mathbf{A}$  is an array of  $mn$  real numbers arranged in  $m$  rows by  $n$  columns:

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix}$$

2. The unknown quantities are represented by the vector  $\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$ .

3. The right hand side of the linear system is represented by the vector  $\mathbf{b} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix}$ .

- **Augmented Matrix:** When we append  $\mathbf{b}$  to the coefficient matrix  $\mathbf{A}$ , we get the augmented matrix  $\widehat{\mathbf{A}} = [\mathbf{A}|\mathbf{b}]$

$$\left( \begin{array}{cccc|c} a_{11} & a_{12} & \cdots & a_{1n} & b_1 \\ a_{21} & a_{22} & \cdots & a_{2n} & b_2 \\ \vdots & & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} & b_m \end{array} \right)$$

### 1.2.8 Finding Solutions to Augmented Matrices and Systems of Equations

- **Row Echelon Form:** Our goal is to translate our augmented matrix or system of equations into row echelon form. This will provide us with the values of the vector  $\mathbf{x}$  which solve the system. We use the row operations to change coefficients in lower triangle of the augmented

matrix to 0. An augmented matrix of the form

$$\left( \begin{array}{cccc|c} \boxed{a'_{11}} & a'_{12} & a'_{13} & \cdots & a'_{1n} & | & b'_1 \\ 0 & \boxed{a'_{22}} & a'_{23} & \cdots & a'_{2n} & | & b'_2 \\ 0 & 0 & \boxed{a'_{33}} & \cdots & a'_{3n} & | & b'_3 \\ 0 & 0 & 0 & \ddots & \vdots & | & \vdots \\ 0 & 0 & 0 & 0 & \boxed{a'_{mn}} & | & b'_m \end{array} \right)$$

is said to be in row echelon form — each row has more leading zeros than the row preceding it.

- **Reduced Row Echelon Form:** We can go one step further and put the matrix into reduced row echelon form. Reduced row echelon form makes the value of  $\mathbf{x}$  which solves the system very obvious. For a system of  $m$  equations in  $m$  unknowns, with no all-zero rows, the reduced row echelon form would be

$$\left( \begin{array}{cccc|c} \boxed{1} & 0 & 0 & 0 & 0 & | & b_1^* \\ 0 & \boxed{1} & 0 & 0 & 0 & | & b_2^* \\ 0 & 0 & \boxed{1} & 0 & 0 & | & b_3^* \\ 0 & 0 & 0 & \ddots & 0 & | & \vdots \\ 0 & 0 & 0 & 0 & \boxed{1} & | & b_m^* \end{array} \right)$$

- **Gaussian and Gauss-Jordan elimination:** We can conduct elementary row operations to get our augmented matrix into row echelon or reduced row echelon form. The methods of transforming a matrix or system into row echelon and reduced row echelon form are referred to as Gaussian elimination and Gauss-Jordan elimination, respectively.
- **Elementary Row Operations:** To do Gaussian and Gauss-Jordan elimination, we use three basic operations to transform the augmented matrix into another augmented matrix that represents an equivalent linear system – equivalent in the sense that the same values of  $x_j$  solve both the original and transformed matrix/system:

1. Interchanging two rows.  $\implies$  Interchanging two equations.
2. Multiplying a row by a constant.  $\implies$  Multiplying both sides of an equation by a constant.
3. Adding two rows to each other.  $\implies$  Adding two equations to each other.

- **Interchanging Rows:** Suppose we have the augmented matrix

$$\widehat{\mathbf{A}} = \left( \begin{array}{cc|c} a_{11} & a_{12} & | & b_1 \\ a_{21} & a_{22} & | & b_2 \end{array} \right)$$

If we interchange the two rows, we get the augmented matrix

$$\left( \begin{array}{cc|c} a_{21} & a_{22} & | & b_2 \\ a_{11} & a_{12} & | & b_1 \end{array} \right)$$

which represents a linear system equivalent to that represented by matrix  $\widehat{\mathbf{A}}$ .

- **Multiplying by a Constant:** If we multiply the second row of matrix  $\widehat{\mathbf{A}}$  by a constant  $c$ , we get the augmented matrix

$$\left( \begin{array}{cc|c} a_{11} & a_{12} & b_1 \\ ca_{21} & ca_{22} & cb_2 \end{array} \right)$$

which represents a linear system equivalent to that represented by matrix  $\widehat{\mathbf{A}}$ .

- **Adding (subtracting) Rows:** If we add (subtract) the first row of matrix  $\widehat{\mathbf{A}}$  to the second, we obtain the augmented matrix

$$\left( \begin{array}{cc|c} a_{11} & a_{12} & b_1 \\ a_{11} + a_{21} & a_{12} + a_{22} & b_1 + b_2 \end{array} \right)$$

which represents a linear system equivalent to that represented by matrix  $\widehat{\mathbf{A}}$ .

Examples: Using Gaussian or Gauss-Jordan elimination, solve the following linear systems by putting them into row echelon or reduced row echelon form:

1.

$$\begin{array}{rcl} x & - & 3y = -3 \\ 2x & + & y = 8 \end{array}$$

2.

$$\begin{array}{rcl} x & + & 2y + 3z = 6 \\ 2x & - & 3y + 2z = 14 \\ 3x & + & y - z = -2 \end{array}$$

### 1.2.9 Rank — and Whether a System Has One, Infinite, or No Solutions

We previously noted that a  $2 \times 2$  system had one, infinite, or no solutions if the two lines intersected, were the same, or were parallel, respectively. More generally, to determine how many solutions exist, we can use information about (1) the number of equations  $m$ , (2) the number of unknowns  $n$ , and (3) the **rank** of the matrix representing the linear system.

- **Rank:** The row rank or column rank of a matrix is the number of nonzero rows or columns in its row echelon form. The rank also corresponds to the maximum number of linearly independent row or column vectors in the matrix. For any matrix  $\mathbf{A}$ , the row rank always equals column rank, and we refer to this number as the rank of  $\mathbf{A}$ .

Examples:

$$1. \begin{pmatrix} 1 & 2 & 3 \\ 0 & 4 & 5 \\ 0 & 0 & 6 \end{pmatrix} \quad \text{Rank=}$$

$$2. \begin{pmatrix} 1 & 2 & 3 \\ 0 & 4 & 5 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{Rank=}$$

$$3. \left( \begin{array}{ccc|c} 1 & 2 & 3 & b_1 \\ 0 & 4 & 5 & b_2 \\ 0 & 0 & 0 & b_3 \end{array} \right), \quad b_i \neq 0 \quad \text{Rank=}$$

Let  $\mathbf{A}$  be the coefficient matrix and  $\widehat{\mathbf{A}} = [\mathbf{A}|\mathbf{b}]$  be the augmented matrix. Then

1.  $\text{rank } \mathbf{A} \leq \text{rank } \widehat{\mathbf{A}}$       Augmenting  $\mathbf{A}$  with  $\mathbf{b}$  can never result in more zero rows than originally in  $\mathbf{A}$  itself. Suppose row  $i$  in  $\mathbf{A}$  is all zeros and that  $b_i$  is non-zero. Augmenting  $\mathbf{A}$  with  $\mathbf{b}$  will yield a non-zero row  $i$  in  $\widehat{\mathbf{A}}$ .
2.  $\text{rank } \mathbf{A} \leq \text{rows } \mathbf{A}$       By definition of “rank.”
3.  $\text{rank } \mathbf{A} \leq \text{cols } \mathbf{A}$       Suppose there are more rows than columns (otherwise the previous rule applies). Each column can contain at most one pivot. By pivoting, all other entries in a column below the pivot are zeroed. Hence, there will only be as many non-zero rows as pivots, which will equal the number of columns.

- **Existence of Solutions:**

1. Exactly one solution:  $\text{rank } \mathbf{A} = \text{rank } \widehat{\mathbf{A}} = \text{rows } \mathbf{A} = \text{cols } \mathbf{A}$   
Necessary condition for a system to have a unique solution: that there be exactly as many equations as unknowns.
2. Infinite solutions:  $\text{rank } \mathbf{A} = \text{rank } \widehat{\mathbf{A}}$  and  $\text{cols } \mathbf{A} > \text{rank } \mathbf{A}$   
If a system has a solution and has more unknowns than equations, then it has infinitely many solutions.

3. No solution:  $\text{rank } \mathbf{A} < \text{rank } \widehat{\mathbf{A}}$

Then there is a zero row  $i$  in  $\mathbf{A}$ 's reduced echelon that corresponds to a non-zero row  $i$  in  $\widehat{\mathbf{A}}$ 's reduced echelon. Row  $i$  of the  $\widehat{\mathbf{A}}$  translates to the equation

$$0x_{i1} + 0x_{i2} + \cdots + 0x_{in} = b'_i$$

where  $b'_i \neq 0$ . Hence the system has no solution.

Examples: Find the rank and number of solutions for the systems of equations below.:

1.

$$\begin{aligned} x - 3y &= -3 \\ 2x + y &= 8 \end{aligned}$$

2.

$$\begin{aligned} x + 2y + 3z &= 6 \\ 2x - 3y + 2z &= 14 \\ 3x + y - z &= -2 \end{aligned}$$

3.

$$\begin{aligned} x + 2y - 3z &= -4 \\ 2x + y - 3z &= 4 \end{aligned}$$

4.

$$\begin{aligned} x_1 + 2x_2 & - 3x_4 + x_5 &= 2 \\ x_1 + 2x_2 + x_3 & - 3x_4 + x_5 + 2x_6 &= 3 \\ x_1 + 2x_2 & - 3x_4 + 2x_5 + x_6 &= 4 \\ 3x_1 + 6x_2 + x_3 & - 9x_4 + 4x_5 + 3x_6 &= 9 \end{aligned}$$

5.

$$\begin{aligned} x + 2y + 3z + 4w &= 5 \\ x + 3y + 5z + 7w &= 11 \\ x & - z - 2w = -6 \end{aligned}$$

### 1.2.10 The Inverse of a Matrix

- **Inverse Matrix:** An  $n \times n$  matrix  $\mathbf{A}$  is **nonsingular** or **invertible** if there exists an  $n \times n$  matrix  $\mathbf{A}^{-1}$  such that

$$\mathbf{A}\mathbf{A}^{-1} = \mathbf{A}^{-1}\mathbf{A} = \mathbf{I}_n$$

where  $\mathbf{A}^{-1}$  is the inverse of  $\mathbf{A}$ . If there is no such  $\mathbf{A}^{-1}$ , then  $\mathbf{A}$  is singular or noninvertible.

Example: Let

$$\mathbf{A} = \begin{pmatrix} 2 & 3 \\ 2 & 2 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} -1 & \frac{3}{2} \\ 1 & -1 \end{pmatrix}$$

Since

$$\mathbf{A}\mathbf{B} = \mathbf{B}\mathbf{A} = \mathbf{I}_n$$

we conclude that  $\mathbf{B}$  is the inverse,  $\mathbf{A}^{-1}$ , of  $\mathbf{A}$  and that  $\mathbf{A}$  is nonsingular.

- Properties of the Inverse:

1. If the inverse exists, it is unique.
2.  $\mathbf{A}$  nonsingular  $\implies \mathbf{A}^{-1}$  nonsingular  $(\mathbf{A}^{-1})^{-1} = \mathbf{A}$
3.  $\mathbf{A}$  nonsingular  $\implies (\mathbf{A}^T)^{-1} = (\mathbf{A}^{-1})^T$

- **Procedure to Find  $\mathbf{A}^{-1}$ :** We know that if  $\mathbf{B}$  is the inverse of  $\mathbf{A}$ , then

$$\mathbf{A}\mathbf{B} = \mathbf{B}\mathbf{A} = \mathbf{I}_n$$

Looking only at the first and last parts of this

$$\mathbf{A}\mathbf{B} = \mathbf{I}_n$$

Solving for  $\mathbf{B}$  is equivalent to solving for  $n$  linear systems, where each column of  $\mathbf{B}$  is solved for the corresponding column in  $\mathbf{I}_n$ . We can solve the systems simultaneously by augmenting  $\mathbf{A}$  with  $\mathbf{I}_n$  and performing Gauss-Jordan elimination on  $\mathbf{A}$ . If Gauss-Jordan elimination on  $[\mathbf{A}|\mathbf{I}_n]$  results in  $[\mathbf{I}_n|\mathbf{B}]$ , then  $\mathbf{B}$  is the inverse of  $\mathbf{A}$ . Otherwise,  $\mathbf{A}$  is singular.

To summarize: To calculate the inverse of  $\mathbf{A}$

1. Form the augmented matrix  $[\mathbf{A}|\mathbf{I}_n]$
2. Using elementary row operations, transform the augmented matrix to reduced row echelon form.
3. The result of step 2 is an augmented matrix  $[\mathbf{C}|\mathbf{B}]$ .
  - (a) If  $\mathbf{C} = \mathbf{I}_n$ , then  $\mathbf{B} = \mathbf{A}^{-1}$ .
  - (b) If  $\mathbf{C} \neq \mathbf{I}_n$ , then  $\mathbf{C}$  has a row of zeros.  $\mathbf{A}$  is singular and  $\mathbf{A}^{-1}$  does not exist.

Example: Find the inverse of  $\mathbf{A} = \begin{pmatrix} 1 & 1 & 1 \\ 0 & 2 & 3 \\ 5 & 5 & 1 \end{pmatrix}$



### 1.2.11 Linear Systems and Inverses

Let's return to the matrix representation of a linear system

$$\mathbf{Ax} = \mathbf{b}$$

If  $\mathbf{A}$  is an  $n \times n$  matrix, then  $\mathbf{Ax} = \mathbf{b}$  is a system of  $n$  equations in  $n$  unknowns. Suppose  $\mathbf{A}$  is nonsingular  $\implies \mathbf{A}^{-1}$  exists. To solve this system, we can premultiply each side by  $\mathbf{A}^{-1}$  and reduce it as follows:

$$\begin{aligned}\mathbf{A}^{-1}(\mathbf{Ax}) &= \mathbf{A}^{-1}\mathbf{b} \\ (\mathbf{A}^{-1}\mathbf{A})\mathbf{x} &= \mathbf{A}^{-1}\mathbf{b} \\ \mathbf{I}_n\mathbf{x} &= \mathbf{A}^{-1}\mathbf{b} \\ \mathbf{x} &= \mathbf{A}^{-1}\mathbf{b}\end{aligned}$$

Hence, given  $\mathbf{A}$  and  $\mathbf{b}$  and given that  $\mathbf{A}$  is nonsingular, then  $\mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$  is a unique solution to this system.

Notice also that the requirements for  $\mathbf{A}$  to be nonsingular correspond to the requirements for a linear system to have a unique solution:  $\text{rank } \mathbf{A} = \text{rows } \mathbf{A} = \text{cols } \mathbf{A}$ .

## 1.2.12 Determinants

- **Singularity:** Determinants can be used to *determine* whether a square matrix is nonsingular.

A square matrix is nonsingular iff its determinant is not zero.

- **Determinant of a  $1 \times 1$  matrix,  $\mathbf{A}$ ,** equals  $a_{11}$

- **Determinant of a  $2 \times 2$  matrix,  $\mathbf{A}$ ,**  $\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}$ :

$$\begin{aligned} (\mathbf{A}) &= |\mathbf{A}| \\ &= a_{11}|a_{22}| - a_{12}|a_{21}| \\ &= a_{11}a_{22} - a_{12}a_{21} \end{aligned}$$

We can extend the second to last equation above to get the definition of the determinant of a  $3 \times 3$  matrix:

$$\begin{aligned} \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} &= a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} \\ &= a_{11}(a_{22}a_{33} - a_{23}a_{32}) - a_{12}(a_{21}a_{33} - a_{23}a_{31}) + a_{13}(a_{21}a_{32} - a_{22}a_{31}) \end{aligned}$$

1. Let's extend this now to any  $n \times n$  matrix. Let's define  $\mathbf{A}_{ij}$  as the  $(n-1) \times (n-1)$  submatrix of  $\mathbf{A}$  obtained by deleting row  $i$  and column  $j$ . Let the  $(i, j)$ th **minor** of  $\mathbf{A}$  be the determinant of  $\mathbf{A}_{ij}$ :

$$M_{ij} = |\mathbf{A}_{ij}|$$

Then for any  $n \times n$  matrix  $\mathbf{A}$

$$|\mathbf{A}| = a_{11}M_{11} - a_{12}M_{12} + \cdots + (-1)^{n+1}a_{1n}M_{1n}$$

Example: Does the following matrix have an inverse?

$$\mathbf{A} = \begin{pmatrix} 1 & 1 & 1 \\ 0 & 2 & 3 \\ 5 & 5 & 1 \end{pmatrix}$$

1. Calculate its determinant.

$$\begin{aligned} &= 1(2 - 15) - 1(0 - 15) + 1(0 - 10) \\ &= -13 + 15 - 10 \\ &= -8 \end{aligned}$$

2. Since  $|\mathbf{A}| \neq 0$ , we conclude that  $\mathbf{A}$  has an inverse.

- **Determinant of Triangular or Diagonal Matrices:** For any upper-triangular, lower-triangular, or diagonal matrix, the determinant is just the product of the diagonal terms.

Example: Suppose we have the following square matrix in row echelon form (i.e., upper triangular)

$$\mathbf{R} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ 0 & r_{22} & r_{23} \\ 0 & 0 & r_{33} \end{pmatrix}$$

Then

$$|\mathbf{R}| = r_{11} \begin{vmatrix} r_{22} & r_{23} \\ 0 & r_{33} \end{vmatrix} = r_{11}r_{22}r_{33}$$

• Properties of Determinants:

1.  $|\mathbf{A}| = |\mathbf{A}^T|$
2. If  $\mathbf{B}$  results from  $\mathbf{A}$  by interchanging two rows, then  $|\mathbf{B}| = -|\mathbf{A}|$ .
3. If two rows of  $\mathbf{A}$  are equal, then  $|\mathbf{A}| = 0$ . (Notice that in this case  $\text{rank } \mathbf{A} \neq$  rows  $\mathbf{A}$ , which was one of the conditions for the existence of a unique solution.)
4. If a row of  $\mathbf{A}$  consists of all zeros, then  $|\mathbf{A}| = 0$ . (Same as 3.)
5. If  $\mathbf{B}$  is obtained by multiplying a row of  $\mathbf{A}$  by a scalar  $s$ , then  $|\mathbf{B}| = s|\mathbf{A}|$ .
6. If  $\mathbf{B}$  is obtained from  $\mathbf{A}$  by adding to the  $i$ th row of  $\mathbf{A}$  the  $j$ th row ( $i \neq j$ ) multiplied by a scalar  $s$ , then  $|\mathbf{B}| = |\mathbf{A}|$ . (i.e., If the row isn't simply multiplied by a scalar and left, then the determinant remains the same.)
7. If no row interchanges and no scalar multiplications of a single row are used to compute the row echelon form  $\mathbf{R}$  from the  $n \times n$  coefficient matrix  $\mathbf{A}$ , then  $|\mathbf{A}| = |\mathbf{R}|$ . (Implied by the previous properties.)
8. A square matrix is nonsingular iff its determinant  $\neq 0$ . (Implied by the previous properties.)
9.  $|\mathbf{AB}| = |\mathbf{A}||\mathbf{B}|$
10. If  $\mathbf{A}$  is nonsingular, then  $|\mathbf{A}| \neq 0$  and  $|\mathbf{A}^{-1}| = \frac{1}{|\mathbf{A}|}$ .

### 1.2.13 Getting Inverse of a Matrix using its Determinant and Matrix of Cofactors

Thus far, we have a number of algorithms to

1. Find the solution of a linear system,
2. Find the inverse of a matrix

but these remain just that — algorithms. At this point, we have no way of telling how the solutions  $x_j$  change as the parameters  $a_{ij}$  and  $b_i$  change, except by changing the values and “rerunning” the algorithms.

With determinants, we can

1. Provide an explicit formula for the inverse, and
2. Provide an explicit formula for the solution of an  $n \times n$  linear system.

Hence, we can examine how changes in the parameters and  $b_i$  affect the solutions  $x_j$ .

- **Determinant Formula for the Inverse of a  $2 \times 2$ :** The determinant of a  $2 \times 2$  matrix  $\mathbf{A} \begin{pmatrix} a & b \\ c & d \end{pmatrix}$  is defined as:

$$\frac{1}{\det(\mathbf{A})} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$$

### 1.2.14 Inverse of Larger Matrices

- **Cofactors and Adjoint Matrices:**

- Define the  $(i, j)$ th **cofactor**  $C_{ij}$  of  $\mathbf{A}$  as  $(-1)^{i+j}M_{ij}$ . Recall that  $M_{ij}$  is the minor of  $\mathbf{A}$ , defined as the determinant of the matrix that results from removing row  $i$  and column  $j$  from  $\mathbf{A}$ .
- Define the **adjoint** of  $\mathbf{A}$  as the  $n \times n$  matrix whose  $(i, j)$ th entry is  $C_{ji}$  (notice the switch in indices!). In other words,  $\text{adj}(\mathbf{A})$  is the transpose of the cofactor matrix of  $\mathbf{A}$ .

- Then the **inverse** of  $\mathbf{A}$  is defined as the reciprocal of the determinant of  $\mathbf{A}$  times its adjoint, given by the formula

$$\mathbf{A}^{-1} = \frac{1}{|\mathbf{A}|} \text{adj } \mathbf{A} = \begin{pmatrix} \frac{C_{11}}{|\mathbf{A}|} & \frac{C_{21}}{|\mathbf{A}|} & \cdots & \frac{C_{n1}}{|\mathbf{A}|} \\ \frac{C_{12}}{|\mathbf{A}|} & \frac{C_{22}}{|\mathbf{A}|} & \cdots & \frac{C_{n2}}{|\mathbf{A}|} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{C_{1n}}{|\mathbf{A}|} & \frac{C_{2n}}{|\mathbf{A}|} & \cdots & \frac{C_{nn}}{|\mathbf{A}|} \end{pmatrix}$$

Examples:

$$\text{Let } \mathbf{A} = \begin{pmatrix} 5 & 1 & 3 \\ 0 & 2 & 3 \\ 5 & 5 & 1 \end{pmatrix}$$

1. Find the determinant of  $\mathbf{A}$ .

$$\begin{aligned} \det \mathbf{A} &= \\ &= \\ &= \\ &= \end{aligned}$$

2. Find the adjoint matrix of  $\mathbf{A}$ .

$$\text{adj}(\mathbf{A}) =$$

3. Find the inverse of  $\mathbf{A}$ .

$$\mathbf{A}^{-1} =$$

## 1.3 Calculus I

### Today's Topics:

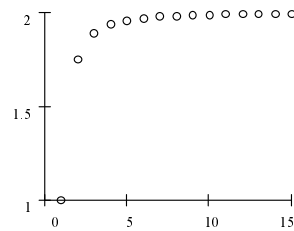
Sequences; Limit of a Sequence; Series; Derivatives; Higher-Order Derivatives; Composite Functions and The Chain Rule; Derivatives of Exp and Ln; Maxima and Minima; Partial Derivatives; L'Hôpital's Rule; Derivative Calculus in 6 Steps

### 1.3.1 Sequences

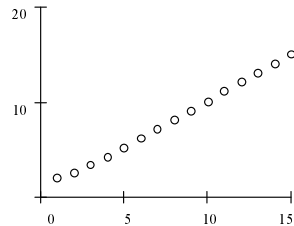
- A **sequence**  $\{y_n\} = \{y_1, y_2, y_3, \dots, y_n\}$  is an ordered set of real numbers, where  $y_1$  is the first term in the sequence and  $y_n$  is the  $n$ th term. Generally, a sequence is **infinite**, that is it extends to  $n = \infty$ . We can also write the sequence as  $\{y_n\}_{n=1}^{\infty}$ .

Examples:

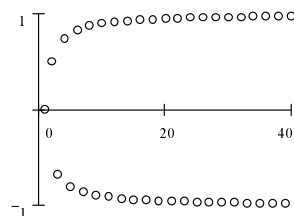
$$1. \{y_n\} = \left\{2 - \frac{1}{n^2}\right\} = \left\{1, \frac{7}{4}, \frac{17}{9}, \frac{31}{16}, \dots\right\}$$



$$2. \{y_n\} = \left\{\frac{n^2+1}{n}\right\} = \left\{2, \frac{5}{2}, \frac{10}{3}, \dots\right\}$$



$$3. \{y_n\} = \left\{(-1)^n \left(1 - \frac{1}{n}\right)\right\} = \left\{0, \frac{1}{2}, -\frac{2}{3}, \frac{3}{4}, \dots\right\}$$



Think of sequences like functions. Before, we had  $y = f(x)$  with  $x$  specified over some domain. Now we have  $\{y_n\} = \{f(n)\}$  with  $n = 1, 2, 3, \dots$

- **Three kinds of sequences:**

1. Sequences like 1 above that converge to a limit.
2. Sequences like 2 above that increase without bound.
3. Sequences like 3 above that neither converge nor increase without bound — alternating over the number line.

- **Boundedness and monotonicity:**
  1. **Bounded:** if  $|y_n| \leq K$  for all  $n$
  2. **Monotonically Increasing:**  $y_{n+1} > y_n$  for all  $n$
  3. **Monotonically Decreasing:**  $y_{n+1} < y_n$  for all  $n$
- **Subsequence:** choose an infinite collection of entries from  $\{y_n\}$ , retaining their order.

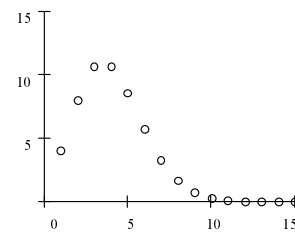
### 1.3.2 The Limit of a Sequence

We're often interested in whether a sequence **converges** to a **limit**. Limits of sequences are conceptually similar to the limits of functions addressed in the previous lecture.

- **Limit of a sequence.** The sequence  $\{y_n\}$  has the limit  $L$ , that is  $\lim_{n \rightarrow \infty} y_n = L$ , if for any  $\epsilon > 0$  there is an integer  $N$  (which depends on  $\epsilon$ ) with the property that  $|y_n - L| < \epsilon$  for each  $n > N$ .  $\{y_n\}$  is said to converge to  $L$ . If the above does not hold, then  $\{y_n\}$  diverges.
- **Uniqueness:** If  $\{y_n\}$  converges, then the limit  $L$  is unique.
- Properties: Let  $\lim_{n \rightarrow \infty} y_n = A$  and  $\lim_{n \rightarrow \infty} z_n = B$ . Then
  1.  $\lim_{n \rightarrow \infty} [\alpha y_n + \beta z_n] = \alpha A + \beta B$
  2.  $\lim_{n \rightarrow \infty} y_n z_n = AB$
  3.  $\lim_{n \rightarrow \infty} \frac{y_n}{z_n} = \frac{A}{B}$ , provided  $B \neq 0$

Examples:

1.  $\lim_{n \rightarrow \infty} \left\{ 2 - \frac{1}{n^2} \right\} = \lim_{n \rightarrow \infty} \{2\} - \lim_{n \rightarrow \infty} \left\{ \frac{1}{n^2} \right\} = 2$
2.  $\lim_{n \rightarrow \infty} \left\{ \frac{4^n}{n!} \right\} = 0$



Finding the limit of a sequence in  $\mathbf{R}^n$  is similar to that in  $\mathbf{R}^1$ .

- **Limit of a sequence of vectors.** The sequence of vectors  $\{\mathbf{y}_n\}$  has the limit  $\mathbf{L}$ , that is  $\lim_{n \rightarrow \infty} \mathbf{y}_n = \mathbf{L}$ , if for any  $\epsilon$  there is an integer  $N$  where  $\|\mathbf{y}_n - \mathbf{L}\| < \epsilon$  for each  $n > N$ . The sequence of vectors  $\{\mathbf{y}_n\}$  is said to converge to the vector  $\mathbf{L}$  — and the distances between  $\mathbf{y}_n$  and  $\mathbf{L}$  converge to zero.

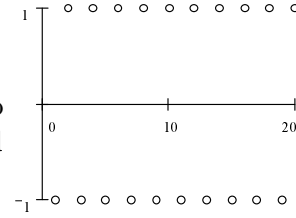
Think of each coordinate of the vector  $\mathbf{y}_n$  as being part of its own sequence over  $n$ . Then a sequence of vectors in  $\mathbf{R}^n$  converges if and only if all  $n$  sequences of its components converge.

Examples:

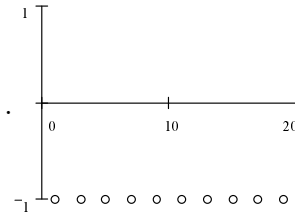
1. The sequence  $\{y_n\}$  where  $y_n = \left(\frac{1}{n}, 2 - \frac{1}{n^2}\right)$  converges to  $(0, 2)$ .
2. The sequence  $\{y_n\}$  where  $y_n = \left(\frac{1}{n}, (-1)^n\right)$  does not converge, since  $\{(-1)^n\}$  does not converge.

- **Bolzano-Weierstrass Theorem:** Any sequence contained in a compact (i.e., closed and bounded) subset of  $\mathbf{R}^n$  contains a convergent subsequence.

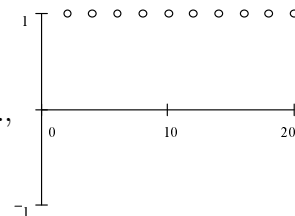
Example: Take the sequence  $\{y_n\} = \{(-1)^n\}$ , which has two accumulating points, but no limit. However, it is both closed and bounded.



The subsequence of  $\{y_n\}$  defined by taking  $n = 1, 3, 5, \dots$  does have a limit:  $-1$ .



As does the subsequence defined by taking  $n = 2, 4, 6, \dots$ , whose limit is  $1$ .



### 1.3.3 Series

- The sum of the terms of a sequence is a **series**. As there are both finite and infinite sequences, there are **finite** and **infinite series**.

The series associated with the sequence  $\{y_n\} = \{y_1, y_2, y_3, \dots, y_n\} = \{y_n\}_{n=1}^{\infty}$  is  $\sum_{n=1}^{\infty} y_n$ . The  $n$ th partial sum  $S_n$  is defined as  $S_n = \sum_{k=1}^n y_k$ , the sum of the first  $n$  terms of the sequence.

- **Convergence:** A series  $\sum y_n$  converges if the sequence of partial sums  $\{S_1, S_2, S_3, \dots\}$  converges, i.e. has a finite limit.
- A **geometric series** is a series that can be written as  $\sum_{n=0}^{\infty} r^n$ , where  $r$  is called the ratio. A geometric series converges to  $\frac{1}{1-r}$  if  $|r| < 1$  and diverges otherwise. For example,  $\sum_{n=0}^{\infty} \frac{1}{2^n} = 2$ .

Examples of other series:

1.  $\sum_{n=0}^{\infty} \frac{1}{n!} = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \dots = e$ .  
This one is especially useful in statistics and probability.
2.  $\sum_{n=1}^{\infty} \frac{1}{n} = \frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \dots = \infty$  (harmonic series)

### 1.3.4 Derivatives

The derivative of  $f$  at  $x$  is its rate of change at  $x$  — i.e., how much  $f(x)$  changes with a change in  $x$ .

- For a line, the derivative is the slope.
- For a curve, the derivative is the slope of the line tangent to the curve at  $x$ .

- **Derivative:** Let  $f$  be a function whose domain includes an open interval containing the point  $x$ . The derivative of  $f$  at  $x$  is given by

$$\begin{aligned} f'(x) &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{(x+h) - x} \\ &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \end{aligned}$$

If  $f'(x)$  exists at a point  $x$ , then  $f$  is said to be **differentiable** at  $x$ . Similarly, if  $f'(x)$  exists for every point along an interval, then  $f$  is differentiable along that interval. For  $f$  to be differentiable at  $x$ ,  $f$  must be both continuous and “smooth” at  $x$ . The process of calculating  $f'(x)$  is called **differentiation**.

- **Notation for derivatives:**

1.  $y', f'(x)$  (Prime or Lagrange Notation)
2.  $Dy, Df(x)$  (Operator Notation)
3.  $\frac{dy}{dx}, \frac{df}{dx}(x)$  (Leibniz’s Notation)

- **Properties of derivatives:** Suppose that  $f$  and  $g$  are differentiable at  $x$  and that  $\alpha$  is a constant. Then the functions  $f \pm g$ ,  $\alpha f$ ,  $f \cdot g$ , and  $f/g$  (provided  $g(x) \neq 0$ ) are also differentiable at  $x$ . Additionally,

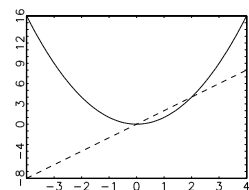
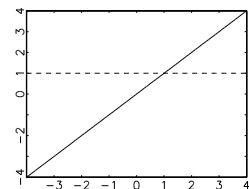
1. **Power rule:**  $[x^k]' = kx^{k-1}$
2. **Sum rule:**  $[f(x) \pm g(x)]' = f'(x) \pm g'(x)$
3. **Constant rule:**  $[\alpha f(x)]' = \alpha f'(x)$
4. **Product rule:**  $[f(x)g(x)]' = f'(x)g(x) + f(x)g'(x)$
5. **Quotient rule:**  $[f(x)/g(x)]' = \frac{f'(x)g(x) - f(x)g'(x)}{[g(x)]^2}, g(x) \neq 0$

Examples:

1.  $f(x) = c$   
 $f'(x) =$

2.  $f(x) = x$   
 $f'(x) =$

3.  $f(x) = x^2$   
 $f'(x) =$

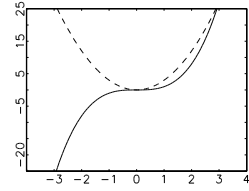


$$4. \quad \begin{aligned} f(x) &= x^3 \\ f'(x) &= \end{aligned}$$

$$5. \quad \begin{aligned} f(x) &= 3x^2 + 2x^{1/3} \\ f'(x) &= \end{aligned}$$

$$6. \quad \begin{aligned} f(x) &= (x^3)(2x^4) \\ f'(x) &= \end{aligned}$$

$$7. \quad \begin{aligned} f(x) &= \frac{x^2+1}{x^2-1} \\ f'(x) &= \end{aligned}$$



### 1.3.5 Higher-Order Derivatives or, Derivatives of Derivatives of Derivatives

We can keep applying the differentiation process to functions that are themselves derivatives. The derivative of  $f'(x)$  with respect to  $x$ , would then be

$$f''(x) = \lim_{h \rightarrow 0} \frac{f'(x+h) - f'(x)}{h}$$

and so on. Similarly, the derivative of  $f''(x)$  would be denoted  $f'''(x)$ .

- **First derivative:**  $f'(x), y', \frac{df(x)}{dx}, \frac{dy}{dx}$
- **Second derivative:**  $f''(x), y'', \frac{d^2f(x)}{dx^2}, \frac{d^2y}{dx^2}$
- **nth derivative:**  $\frac{d^n f(x)}{dx^n}, \frac{d^n y}{dx^n}$

Example:

$$\begin{aligned} f(x) &= x^3 \\ f'(x) &= 3x^2 \\ f''(x) &= 6x \\ f'''(x) &= 6 \\ f''''(x) &= 0 \end{aligned}$$

### 1.3.6 Composite Functions and the Chain Rule

- **Composite functions** are formed by substituting one function into another and are denoted by

$$(f \circ g)(x) = f[g(x)]$$

To form  $f[g(x)]$ , the range of  $g$  must be contained (at least in part) within the domain of  $f$ . The domain of  $f \circ g$  consists of all the points in the domain of  $g$  for which  $g(x)$  is in the domain of  $f$ .

Examples:

1.  $f(x) = \ln x,$

$$g(x) = x^2$$

$$(f \circ g)(x) = \ln x^2,$$

$$(g \circ f)(x) = [\ln x]^2,$$

Notice that  $f \circ g$  and  $g \circ f$  are not the same functions.

2.  $f(x) = 4 + \sin x,$

$$g(x) = \sqrt{1 - x^2},$$

$$(f \circ g)(x) = 4 + \sin \sqrt{1 - x^2},$$

$(g \circ f)(x)$  does not exist.  $\sqrt{1 - (4 + \sin(x))^2}$  is not a real number because  $1 - (4 + \sin(x))^2$  is always negative.

- **Chain Rule:** Let  $y = (f \circ g)(x) = f[g(x)]$ . The derivative of  $y$  with respect to  $x$  is

$$\frac{d}{dx}\{f[g(x)]\} = f'[g(x)]g'(x)$$

which can also be written as

$$\frac{dy}{dx} = \frac{dy}{dg(x)} \frac{dg(x)}{dx}$$

(Note: the above does not imply that the  $dg(x)$ 's cancel out, as in fractions. They are part of the derivative notation and you can't separate them out or cancel them.)

The chain rule can be thought of as the derivative of the "outside" times the derivative of the "inside," remembering that the derivative of the outside function is evaluated at the value of the inside function.

- **Generalized Power Rule:** If  $y = [g(x)]^k$ , then  $dy/dx = k[g(x)]^{k-1}g'(x)$ .

Examples:

1. Find  $dy/dx$  for  $y = (3x^2 + 5x - 7)^6$ . Let  $f(z) = z^6$  and  $z = g(x) = 3x^2 + 5x - 7$ . Then,  $y = f[g(x)]$  and

$$\begin{aligned} \frac{dy}{dx} &= \\ &= \\ &= \end{aligned}$$

2. Find  $dy/dx$  for  $y = \sin(x^3 + 4x)$ . (Note: the derivative of  $\sin x$  is  $\cos x$ .) Let  $f(z) = \sin z$  and  $z = g(x) = x^3 + 4x$ . Then,  $y = f[g(x)]$  and

$$\begin{aligned} \frac{dy}{dx} &= \\ &= \\ &= \end{aligned}$$

### 1.3.7 Derivatives of Euler's number and natural logs

- **Derivatives of Exp or  $e$ :**

1.  $\frac{d}{dx}e^x = e^x$
2.  $\frac{d}{dx}\alpha e^x = \alpha e^x$
3.  $\frac{d^n}{dx^n}\alpha e^x = \alpha e^x$
4.  $\frac{d}{dx}e^{u(x)} = e^{u(x)}u'(x)$

Examples: Find  $dy/dx$  for

1.  $y = e^{-3x}$
2.  $y = e^{x^2}$
3.  $y = e^{\sin 2x}$

- **Derivatives of Ln:**

1.  $\frac{d}{dx} \ln x = \frac{1}{x}$
2.  $\frac{d}{dx} \ln x^k = \frac{d}{dx} k \ln x = \frac{k}{x}$
3.  $\frac{d}{dx} \ln u(x) = \frac{u'(x)}{u(x)}$  (by the chain rule)
4. For any positive base  $b$ ,  $\frac{d}{dx} b^x = (\ln b)(b^x)$ .

Examples: Find  $dy/dx$  for

1.  $y = \ln(x^2 + 9)$
2.  $y = \ln(\ln x)$
3.  $y = (\ln x)^2$
4.  $y = \ln e^x$

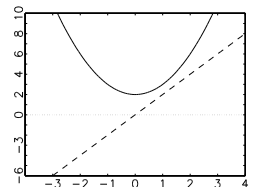
### 1.3.8 Applications of the Derivative: Maxima and Minima

The first derivative,  $f'(x)$ , identifies whether the function  $f(x)$  at the point  $x$  is increasing or decreasing at  $x$ .

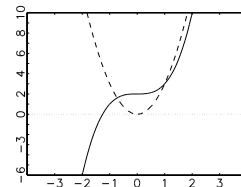
- |  |             |
|--|-------------|
| 1. <b>Increasing:</b>                        | $f'(x) > 0$ |
| 2. <b>Decreasing:</b>                        | $f'(x) < 0$ |
| 3. <b>Neither increasing nor decreasing:</b> | $f'(x) = 0$ |
| i.e. a maximum, minimum, or saddle point     |             |

Examples:

1.  $f(x) = x^2 + 2$ ,  $f'(x) = 2x$



$$2. f(x) = x^3 + 2, f'(x) = 3x^2$$



The second derivative  $f''(x)$  identifies whether the function  $f(x)$  at the point  $x$  is

1. **Concave down:**  $f''(x) < 0$
2. **Concave up:**  $f''(x) > 0$

- **Maximum (Minimum):**  $x_0$  is a **local maximum (minimum)** if  $f(x_0) > f(x)$  ( $f(x_0) < f(x)$ ) for all  $x$  within some open interval containing  $x_0$ .  $x_0$  is a **global maximum (minimum)** if  $f(x_0) > f(x)$  ( $f(x_0) < f(x)$ ) for all  $x$  in the domain of  $f$ .
- **Critical points:** Given the function  $f$  defined over domain  $D$ , all of the following are defined as **critical points**:
  1. Any interior point of  $D$  where  $f'(x) = 0$ .
  2. Any interior point of  $D$  where  $f'(x)$  does not exist.
  3. Any endpoint that is in  $D$ .

The maxima and minima will be a subset of the critical points.

- **Second Derivative Test of Maxima/Minima:** We can use the second derivative to tell us whether a point is a maximum or minimum of  $f(x)$ .

- |                        |                              |
|------------------------|------------------------------|
| <b>Local Maximum:</b>  | $f'(x) = 0$ and $f''(x) < 0$ |
| <b>Local Minimum:</b>  | $f'(x) = 0$ and $f''(x) > 0$ |
| <b>Need more info:</b> | $f'(x) = 0$ and $f''(x) = 0$ |

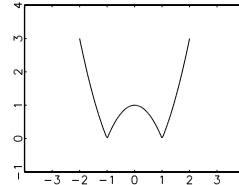
- **Global Maxima and Minima.** Sometimes no global max or min exists — e.g.,  $f(x)$  not bounded above or below. However, there are three situations where we can fairly easily identify global max or min.
  1. **Functions with only one critical point.** If  $x_0$  is a local max or min of  $f$  and it is the only critical point, then it is the global max or min.
  2. **Globally concave up or concave down functions.** If  $f''(x)$  is never zero, then there is at most one critical point. That critical point is a global maximum if  $f'' < 0$  and a global minimum if  $f'' > 0$ .
  3. **Functions over closed and bounded intervals** must have both a global maximum and a global minimum.

Examples: Find any critical points and identify whether they're a max, min, or saddle point:

1.  $f(x) = x^2 + 2$   
 $f'(x) = 2x$   
 $f''(x) = 2$

$$2. \begin{aligned} f(x) &= x^3 + 2 \\ f'(x) &= 3x^2 \\ f''(x) &= 6x \end{aligned}$$

$$3. \begin{aligned} f(x) &= |x^2 - 1|, x \in [-2, 2] \\ f'(x) &= \begin{cases} 2x & -2 < x < -1, 1 < x < 2 \\ -2x & -1 < x < 1 \end{cases} \\ f''(x) &= \begin{cases} 2 & -2 < x < -1, 1 < x < 2 \\ -2 & -1 < x < 1 \end{cases} \end{aligned}$$



### 1.3.9 Partial Derivatives

Suppose we have a function  $f$  now of two (or more) variables and we want to determine the rate of change relative to one of the variables. To do so, we would find its partial derivative, which is defined similar to the derivative of a function of one variable.

- **Partial Derivative:** Let  $f$  be a function of the variables  $(x_1, \dots, x_n)$ . The partial derivative of  $f$  with respect to  $x_i$  is

$$\frac{\partial f}{\partial x_i}(x_1, \dots, x_n) = \lim_{h \rightarrow 0} \frac{f(x_1, \dots, x_i + h, \dots, x_n) - f(x_1, \dots, x_i, \dots, x_n)}{h}$$

Only the  $i$ th variable changes — the others are treated as constants.

We can take higher-order partial derivatives, like we did with functions of a single variable, except now we the higher-order partials can be with respect to multiple variables.

Examples:

$$1. \begin{aligned} f(x, y) &= x^2 + y^2 \\ \frac{\partial f}{\partial x}(x, y) &= \\ \frac{\partial f}{\partial y}(x, y) &= \\ \frac{\partial^2 f}{\partial x^2}(x, y) &= \\ \frac{\partial^2 f}{\partial x \partial y}(x, y) &= \end{aligned}$$

$$\begin{aligned}
2. \quad & f(x, y) = x^3y^4 + e^x - \ln y \\
& \frac{\partial f}{\partial x}(x, y) = \\
& \frac{\partial f}{\partial y}(x, y) = \\
& \frac{\partial^2 f}{\partial x^2}(x, y) = \\
& \frac{\partial^2 f}{\partial x \partial y}(x, y) =
\end{aligned}$$

### 1.3.10 L'Hôpital's Rule

In studying limits, we saw that  $\lim_{x \rightarrow c} f(x)/g(x) = \left( \lim_{x \rightarrow c} f(x) \right) / \left( \lim_{x \rightarrow c} g(x) \right)$ , provided that  $\lim_{x \rightarrow c} g(x) \neq 0$ .

- If both  $\lim_{x \rightarrow c} f(x) = 0$  and  $\lim_{x \rightarrow c} g(x) = 0$ , then we get an **indeterminate form** of the type  $0/0$  as  $x \rightarrow c$ . However, a limit may still exist. We can use L'Hôpital's rule to find the limit.
- **L'Hôpital's Rule:** Suppose  $f$  and  $g$  are differentiable on some interval  $a < x < b$  and that either

1.  $\lim_{x \rightarrow a^+} f(x) = 0$  and  $\lim_{x \rightarrow a^+} g(x) = 0$ , or
2.  $\lim_{x \rightarrow a^+} f(x) = \pm\infty$  and  $\lim_{x \rightarrow a^+} g(x) = \pm\infty$

Suppose further that  $g'(x)$  is never zero on  $a < x < b$  and that

$$\lim_{x \rightarrow a^+} \frac{f'(x)}{g'(x)} = L$$

then

$$\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)} = L$$

And if  $\lim_{x \rightarrow a} f'(x)/g'(x) = 0/0$  or  $\pm\infty/\pm\infty$  then you can apply L'Hôpital's rule a second time, and continue applying it until you have a solution.

Examples: Use L'Hôpital's rule to find the following limits:

1.  $\lim_{x \rightarrow 0^+} \frac{\ln(1+x^2)}{x^3}$
2.  $\lim_{x \rightarrow 0^+} \frac{e^{1/x}}{1/x}$
3.  $\lim_{x \rightarrow 2} \frac{x-2}{(x+6)^{1/3}-2}$

**1.3.11 Summary: Derivative calculus in 6 steps**

With these six rules (and decent algebra and trigonometry skills) you can figure out the derivative of anything.

1. Sum rule:  $[f(x) \pm g(x)]' = f'(x) \pm g'(x)$
2. Product rule:  $[f(x)g(x)]' = f'(x)g(x) + f(x)g'(x)$
3. Power rule:  $[x^k]' = kx^{k-1}$
4. Chain rule:  $\frac{d}{dx}\{f[g(x)]\} = f'[g(x)]g'(x)$
5.  $e^x$ :  $\frac{d}{dx}e^x = e^x$
6. Trig identity:  $\frac{d}{dx} \sin(x) = \cos(x)$

## 1.4 Calculus II

**Today's Topics:** The Indefinite Integral: The Antiderivative; Common Rules of Integration; The Definite Integral: The Area under the Curve; Integration by Substitution; Integration by Parts

### 1.4.1 The Indefinite Integral: The Antiderivative

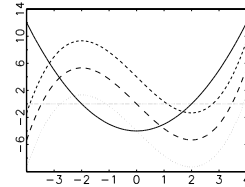
So far, we've been interested in finding the derivative  $g = f'$  of a function  $f$ . However, sometimes we're interested in exactly the reverse: finding the function  $f$  for which  $g$  is its derivative. We refer to  $f$  as the **antiderivative** of  $g$ .

Let  $DF$  be the derivative of  $F$ . And let  $DF(x)$  be the derivative of  $F$  evaluated at  $x$ . Then the antiderivative is denoted by  $D^{-1}$  (i.e., the inverse derivative). If  $DF = f$ , then  $F = D^{-1}f$ .

- **Indefinite Integral:** Equivalently, if  $F$  is the antiderivative of  $f$ , then  $F$  is also called the indefinite integral of  $f$  and written  $F(x) = \int f(x)dx$ .

Examples:

1.  $\int \frac{1}{x^2} dx =$
2.  $\int 3e^{3x} dx =$
3.  $\int (x^2 - 4) dx =$



Notice from these examples that while there is only a single derivative for any function, there are multiple antiderivatives: one for any arbitrary constant  $c$ .  $c$  just shifts the curve up or down on the  $y$ -axis. If more info is present about the antiderivative — e.g., that it passes through a particular point — then we can solve for a specific value of  $c$ .

### 1.4.2 Common Rules of Integration

- $\int af(x)dx = a \int f(x)dx$
- $\int [f(x) + g(x)]dx = \int f(x)dx + \int g(x)dx$
- $\int x^n dx = \frac{1}{n+1}x^{n+1} + c$
- $\int e^x dx = e^x + c$
- $\int \frac{1}{x} dx = \ln x + c$
- $\int e^{f(x)} f'(x) dx = e^{f(x)} + c$
- $\int [f(x)]^n f'(x) dx = \frac{1}{n+1} [f(x)]^{n+1} + c$
- $\int \frac{f'(x)}{f(x)} dx = \ln f(x) + c$

Examples:

1.  $\int 3x^2 dx = 3 \int x^2 dx =$
2.  $\int (2x + 1) dx =$
3.  $\int e^x e^{e^x} dx =$

### 1.4.3 The Definite Integral: The Area under the Curve

- **Riemann Sum:** Suppose we want to determine the area  $A(R)$  of a region  $R$  defined by a curve  $f(x)$  and some interval  $a \leq x \leq b$ . One way to calculate the area would be to divide the interval  $a \leq x \leq b$  into  $n$  subintervals of length  $\Delta x$  and then approximate the region with a series of rectangles, where the base of each rectangle is  $\Delta x$  and the height is  $f(x)$  at the midpoint of that interval.  $A(R)$  would then be approximated by the area of the union of the rectangles, which is given by

$$S(f, \Delta x) = \sum_{i=1}^n f(x_i) \Delta x$$

and is called a Riemann sum.

As we decrease the size of the subintervals  $\Delta x$ , making the rectangles “thinner,” we would expect our approximation of the area of the region to become closer to the true area. This gives the limiting process

$$A(R) = \lim_{\Delta x \rightarrow 0} \sum_{i=1}^n f(x_i) \Delta x$$

- **Riemann Integral:** If for a given function  $f$  the Riemann sum approaches a limit as  $\Delta x \rightarrow 0$ , then that limit is called the Riemann integral of  $f$  from  $a$  to  $b$ . Formally,

$$\int_a^b f(x) dx = \lim_{\Delta x \rightarrow 0} \sum_{i=1}^n f(x_i) \Delta x$$

- **Definite Integral:** We use the notation  $\int_a^b f(x) dx$  to denote the definite integral of  $f$  from  $a$  to  $b$ . In words, the definite integral  $\int_a^b f(x) dx$  is the area under the “curve”  $f(x)$  from  $x = a$  to  $x = b$ .

- **First Fundamental Theorem of Calculus:** Let the function  $f$  be bounded on  $[a, b]$  and continuous on  $(a, b)$ . Then the function

$$F(x) = \int_a^x f(t) dt, \quad a \leq x \leq b$$

has a derivative at each point in  $(a, b)$  and

$$F'(x) = f(x), \quad a < x < b$$

This last point shows that differentiation is the inverse of integration.

- **Second Fundamental Theorem of Calculus:** Let the function  $f$  be bounded on  $[a, b]$  and continuous on  $(a, b)$ . Let  $F$  be any function that is continuous on  $[a, b]$  such that  $F'(x) = f(x)$  on  $(a, b)$ . Then

$$\int_a^b f(x)dx = F(b) - F(a)$$

- **Procedure to calculate a “simple” definite integral  $\int_a^b f(x)dx$ :**

1. Find the indefinite integral  $F(x)$ .
2. Evaluate  $F(b) - F(a)$ .

Examples:

1.  $\int_1^3 3x^2 dx =$
2.  $\int_{-2}^2 e^x e^{e^x} dx =$

- Properties of Definite Integrals:

1.  $\int_a^a f(x)dx = 0$                       There is no area below a point.
2.  $\int_a^b f(x)dx = -\int_b^a f(x)dx$               Reversing the limits changes the sign of the integral.
3.  $\int_a^b [\alpha f(x) + \beta g(x)]dx = \alpha \int_a^b f(x)dx + \beta \int_a^b g(x)dx$
4.  $\int_a^b f(x)dx + \int_b^c f(x)dx = \int_a^c f(x)dx$

Examples:

1.  $\int_1^1 3x^2 dx =$
2.  $\int_0^4 (2x + 1)dx =$
3.  $\int_{-2}^0 e^x e^{e^x} dx + \int_0^2 e^x e^{e^x} dx =$

### 1.4.4 Integration by Substitution

- Sometimes the integrand doesn't appear integrable using common rules and antiderivatives. A method one might try is **integration by substitution**, which is related to the Chain Rule.

Suppose we want to find the indefinite integral  $\int g(x)dx$  and assume we can identify a function  $u(x)$  such that  $g(x) = f[u(x)]u'(x)$ . Let's refer to the antiderivative of  $f$  as  $F$ . Then the chain rule tells us that  $\frac{d}{dx}F[u(x)] = f[u(x)]u'(x)$ . So,  $F[u(x)]$  is the antiderivative of  $g$ . We can then write

$$\int g(x)dx = \int f[u(x)]u'(x)dx = \int \frac{d}{dx}F[u(x)]dx = F[u(x)] + c$$

- **Procedure to determine the indefinite integral  $\int g(x)dx$  by the method of substitution:**
  1. Identify some part of  $g(x)$  that might be simplified by substituting in a single variable  $u$  (which will then be a function of  $x$ ).
  2. Determine if  $g(x)dx$  can be reformulated in terms of  $u$  and  $du$ .
  3. Solve the indefinite integral.
  4. Substitute back in for  $x$

Substitution can also be used to calculate a definite integral. Using the same procedure as above,

$$\int_a^b g(x)dx = \int_c^d f(u)du = F(d) - F(c)$$

where  $c = u(a)$  and  $d = u(b)$ .

Examples:

1.  $\int x^2\sqrt{x+1}dx$

The problem here is the  $\sqrt{x+1}$  term. However, if the integrand had  $\sqrt{x}$  times some polynomial, then we'd be in business. Let's try  $u = x + 1$ . Then  $x = u - 1$  and  $dx = du$ . Substituting these into the above equation, we get

$$\begin{aligned} \int x^2\sqrt{x+1}dx &= \int (u-1)^2\sqrt{u}du \\ &= \int (u^2 - 2u + 1)u^{1/2}du \\ &= \int (u^{5/2} - 2u^{3/2} + u^{1/2})du \end{aligned}$$

We can easily integrate this, since it's just a polynomial. Doing so and substituting  $u = x + 1$  back in, we get

$$\int x^2\sqrt{x+1}dx = 2(x+1)^{3/2} \left[ \frac{1}{7}(x+1)^2 - \frac{2}{5}(x+1) + \frac{1}{3} \right] + c$$

2. For the above problem, we could have also used the substitution  $u = \sqrt{x+1}$ . Then  $x = u^2 - 1$  and  $dx = 2u du$ . Substituting these in, we get

$$\int x^2 \sqrt{x+1} dx = \int (u^2 - 1)^2 u 2u du$$

which when expanded is again a polynomial and gives the same result as above.

3.  $\int_0^1 \frac{5e^{2x}}{(1+e^{2x})^{1/3}} dx$

When an expression is raised to a power, it's often helpful to use this expression as the basis for a substitution. So, let  $u = 1 + e^{2x}$ . Then  $du = 2e^{2x} dx$  and we can set  $5e^{2x} dx = 5du/2$ . Additionally,  $u = 2$  when  $x = 0$  and  $u = 1 + e^2$  when  $x = 1$ . Substituting all of this in, we get

$$\begin{aligned} \int_0^1 \frac{5e^{2x}}{(1+e^{2x})^{1/3}} dx &= \frac{5}{2} \int_2^{1+e^2} \frac{du}{u^{1/3}} \\ &= \frac{5}{2} \int_2^{1+e^2} u^{-1/3} du \\ &= \frac{15}{4} u^{2/3} \Big|_2^{1+e^2} \\ &= 9.53 \end{aligned}$$

#### 1.4.5 Integration by Parts, or Ultraviolet Voodoo

- Another useful integration technique is **integration by parts**, which is related to the Product Rule of differentiation. The product rule states that

$$\frac{d}{dx}(uv) = u \frac{dv}{dx} + v \frac{du}{dx}$$

Integrating this and rearranging, we get

$$\int u \frac{dv}{dx} dx = uv - \int v \frac{du}{dx} dx$$

or

$$\int u(x)v'(x) dx = u(x)v(x) - \int v(x)u'(x) dx$$

More frequently remembered as

$$\int u dv = uv - \int v du$$

where  $du = u'(x)dx$  and  $dv = v'(x)dx$ .

For definite integrals:  $\int_a^b u \frac{dv}{dx} dx = uv \Big|_a^b - \int_a^b v \frac{du}{dx} dx$

Our goal here is to find expressions for  $u$  and  $dv$  that, when substituted into the above equation, yield an expression that's more easily evaluated.

Examples:

1.  $\int x e^{ax} dx$

Let  $u = x$  and  $dv = e^{ax} dx$ . Then  $du = dx$  and  $v = (1/a)e^{ax}$ . Substituting this into the integration by parts formula, we obtain

$$\begin{aligned} \int x e^{ax} dx &= uv - \int v du \\ &= x \left( \frac{1}{a} e^{ax} \right) - \int \frac{1}{a} e^{ax} dx \\ &= \frac{1}{a} x e^{ax} - \frac{1}{a^2} e^{ax} + c \end{aligned}$$

2.  $\int x^n e^{ax} dx$

$$\begin{aligned} \int x^n e^{ax} dx &= \\ &= \\ &= \end{aligned}$$

3.  $\int x^3 e^{-x^2} dx$

$$\begin{aligned} \int x^3 e^{-x^2} dx &= \\ &= \\ &= \\ &= \end{aligned}$$

## 1.5 Unconstrained and Constrained Optimization

**Today's Topics**<sup>7</sup>: • Taylor Series Approximation • Quadratic Forms • Definiteness of Quadratic Forms • Maxima and Minima in  $\mathbf{R}^n$  • First Order Conditions • Second Order Conditions • Global Maxima and Minima • Constrained Optimization • Equality Constraints • Inequality Constraints • Kuhn-Tucker Conditions

### 1.5.1 Quadratic Forms

- Quadratic forms important because
  1. Approximates local curvature around a point — e.g., used to identify max vs min vs saddle point.
  2. Simple, so easy to deal with.
  3. Have a matrix representation.
- **Quadratic Form:** A polynomial where each term is a monomial of degree 2 in any number of variables:

$$\text{One variable: } Q(x_1) = a_{11}x_1^2$$

$$\text{Two variables: } Q(x_1, x_2) = a_{11}x_1^2 + a_{12}x_1x_2 + a_{22}x_2^2$$

$$N \text{ variables: } Q(x_1, \dots, x_n) = \sum_{i \leq j} a_{ij}x_i x_j$$

which can be written in matrix terms:

$$\text{One variable: } Q(\mathbf{x}) = x_1^T a_{11} x_1$$

$$N \text{ variables: } Q(\mathbf{x}) = \begin{pmatrix} x_1 & x_2 & \dots & x_n \end{pmatrix} \begin{pmatrix} a_{11} & \frac{1}{2}a_{12} & \dots & \frac{1}{2}a_{1n} \\ \frac{1}{2}a_{12} & a_{22} & \dots & \frac{1}{2}a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{2}a_{1n} & \frac{1}{2}a_{2n} & \dots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

$$= \mathbf{x}^T \mathbf{A} \mathbf{x}$$

Examples:

1. Quadratic on  $\mathbf{R}^2$ :

$$\begin{aligned} Q(x_1, x_2) &= \begin{pmatrix} x_1 & x_2 \end{pmatrix} \begin{pmatrix} a_{11} & \frac{1}{2}a_{12} \\ \frac{1}{2}a_{12} & a_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \\ &= a_{11}x_1^2 + a_{12}x_1x_2 + a_{22}x_2^2 \end{aligned}$$

2. Quadratic on  $\mathbf{R}^3$ :  $Q(x_1, x_2, x_3) =$

<sup>7</sup>Much of the material and examples for this lecture are taken from Simon & Blume (1994) *Mathematics for Economists* and Ecker & Kupferschmid (1988) *Introduction to Operations Research*.

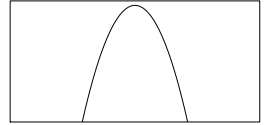
### 1.5.2 Concavity of Quadratic Forms

Concavity helps identify the curvature of a function,  $f(x)$ , in 2 dimensional space.

- **Concave:** A function  $f$  is strictly concave over the set  $S$  if  $\forall x_1, x_2 \in S$  and  $\forall a \in (0, 1)$ ,

$$f(ax_1 + (1 - a)x_2) > af(x_1) + (1 - a)f(x_2)$$

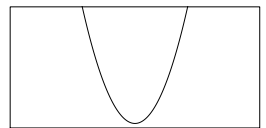
Any line connecting two points on a concave function will lie *below* the function.



- **Convex:** A function  $f$  is strictly convex over the set  $S$  if  $\forall x_1, x_2 \in S$  and  $\forall a \in (0, 1)$ ,

$$f(ax_1 + (1 - a)x_2) < af(x_1) + (1 - a)f(x_2)$$

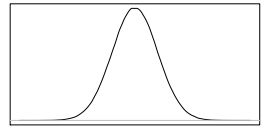
Any line connecting two points on a convex function will lie *above* the function.



- **Quasiconcave:** A function  $f$  is quasiconcave over the set  $S$  if  $\forall x_1, x_2 \in S$  and  $\forall a \in (0, 1)$ ,

$$f(ax_1 + (1 - a)x_2) \geq \min(f(x_1), f(x_2))$$

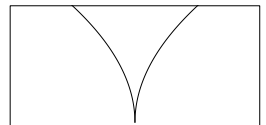
No matter what two points you select, the *lowest* valued point will always be an end point.



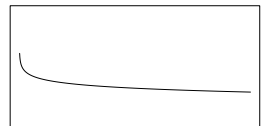
- **Quasiconvex:** A function  $f$  is quasiconvex over the set  $S$  if  $\forall x_1, x_2 \in S$  and  $\forall a \in (0, 1)$ ,

$$f(ax_1 + (1 - a)x_2) \leq \max(f(x_1), f(x_2))$$

No matter what two points you select, the *highest* valued point will always be an end point.



- **Quasilinear:** A function that is both quasiconvex and quasiconcave is quasilinear.



- **Second Derivative Test of Concavity:** The second derivative can be used to understand concavity. If,  $f''(x) < 0 \Rightarrow$  Concave  
 $f''(x) > 0 \Rightarrow$  Convex

### 1.5.3 Definiteness of Quadratic Forms

Definiteness helps identify the curvature of a function,  $Q(\mathbf{x})$ , in  $n$  dimensional space.

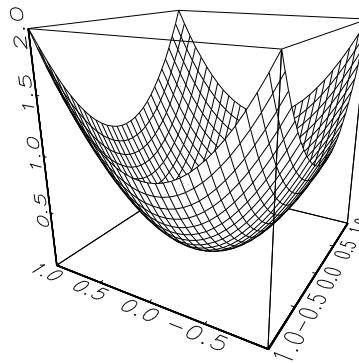
- **Definiteness:** By definition, a quadratic form always takes on the value of zero when  $x = 0$ ,  $Q(\mathbf{x}) = 0$  at  $\mathbf{x} = 0$ . The definiteness of the matrix  $\mathbf{A}$  is determined by whether the quadratic form  $Q(\mathbf{x}) = \mathbf{x}^T \mathbf{A} \mathbf{x}$  is greater than zero, less than zero, or sometimes both over all  $\mathbf{x} \neq 0$ .

- |  |   |         |
|--|---|---------|
| 1. Positive Definite                         | $\mathbf{x}^T \mathbf{A} \mathbf{x} > 0, \quad \forall \mathbf{x} \neq 0$   | Min     |
| ex: $Q(x_1, x_2) = x_1^2 + x_2^2$            |   |         |
| 2. Positive Semidefinite                     | $\mathbf{x}^T \mathbf{A} \mathbf{x} \geq 0, \quad \forall \mathbf{x} \neq 0$  |         |
| ex: $Q(x_1, x_2) = x_1^2 + 2x_1x_2 + x_2^2$  |   |         |
| 3. Negative Definite                         | $\mathbf{x}^T \mathbf{A} \mathbf{x} < 0, \quad \forall \mathbf{x} \neq 0$   | Max     |
| ex: $Q(x_1, x_2) = -x_1^2 - x_2^2$           |   |         |
| 4. Negative Semidefinite                     | $\mathbf{x}^T \mathbf{A} \mathbf{x} \leq 0, \quad \forall \mathbf{x} \neq 0$  |         |
| ex: $Q(x_1, x_2) = -x_1^2 - 2x_1x_2 - x_2^2$ |   |         |
| 5. Indefinite                                | $\mathbf{x}^T \mathbf{A} \mathbf{x} > 0$ for some $\mathbf{x} \neq 0$ and<br>$\mathbf{x}^T \mathbf{A} \mathbf{x} < 0$ for other $\mathbf{x} \neq 0$ | Neither |
| ex: $Q(x_1, x_2) = x_1^2 - x_2^2$            |   |         |

Examples:

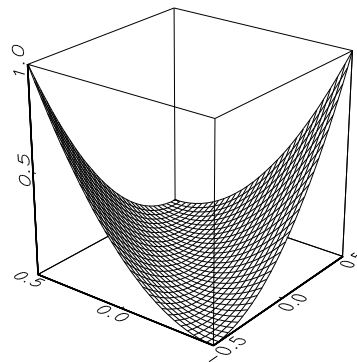
1. Positive Definite:

$$\begin{aligned} Q(\mathbf{x}) &= \mathbf{x}^T \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{x} \\ &= x_1^2 + x_2^2 \end{aligned}$$



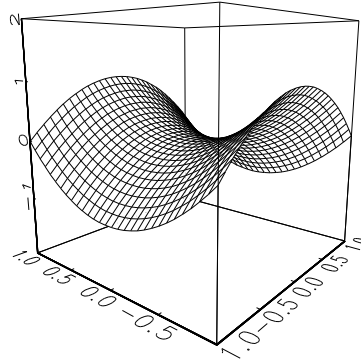
2. Positive Semidefinite:

$$\begin{aligned} Q(\mathbf{x}) &= \mathbf{x}^T \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \mathbf{x} \\ &= (x_1 - x_2)^2 \end{aligned}$$



3. Indefinite:

$$\begin{aligned} Q(\mathbf{x}) &= \mathbf{x}^T \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \mathbf{x} \\ &= x_1^2 - x_2^2 \end{aligned}$$



### 1.5.4 Test for Definiteness using Principal Minors

**$k$ th Order Principal Minors:** the *determinants* of the  $k \times k$  submatrices of an  $n \times n$  matrix,  $\mathbf{A}$ , obtained by deleting  $n - k$  columns and the same  $n - k$  rows from matrix  $\mathbf{A}$ .

Example: For a  $3 \times 3$  matrix  $\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$

1. First order principle minors:

$$|a_{11}|, \quad |a_{22}|, \quad |a_{33}|$$

2. Second order principle minors:

3. Third order principle minor:

- **$k$ th Leading Principal Minor,  $M_k$ :** the determinant of the  $k \times k$  submatrix obtained by deleting the last  $n - k$  rows and columns from the  $n \times n$  matrix,  $\mathbf{A}$ .

Example: For a  $3 \times 3$  matrix  $\mathbf{A}$ , the three leading principal minors are

$$M_1 = \quad M_2 = \quad M_3 =$$

- **Theorem:** If  $\mathbf{A}$  is an  $n \times n$  symmetric matrix, then

1.  $M_k > 0, k = 1, \dots, n$   $\implies$  Positive Definite
2.  $M_k < 0$ , for odd  $k$  and  $M_k > 0$ , for even  $k$   $\implies$  Negative Definite
3.  $M_k \neq 0, k = 1, \dots, n$ , but does not fit the pattern of 1 or 2.  $\implies$  Indefinite.

If some leading principle minor is zero, but all others fit the pattern of the preceding conditions 1 or 2, then:

- |   |            |                       |
|---|------------|-----------------------|
| 4. Every principal minor $\geq 0$   | $\implies$ | Positive Semidefinite |
| 5. Every principal minor of odd order $\leq 0$ and every principal minor of even order $\geq 0$ | $\implies$ | Negative Semidefinite |

Example:  $\mathbf{A} = \begin{pmatrix} 2 & 3 \\ 3 & 7 \end{pmatrix}$  and  $\mathbf{A} = \begin{pmatrix} 2 & 4 \\ 4 & 7 \end{pmatrix}$

Definiteness of  $\mathbf{A} =$

Definiteness of  $\mathbf{B} =$

### 1.5.5 Maxima and Minima in $\mathbf{R}^n$

- **Conditions for Extrema:** The conditions for extrema are similar to those for functions on  $\mathbf{R}^1$ . Let  $f(\mathbf{x})$  be a function of  $n$  variables. Let  $B(\mathbf{x}, \epsilon)$  be the  $\epsilon$ -ball about the point  $\mathbf{x}$  (an area around  $\mathbf{x}$ ). Then

- |   |            |                  |
|---|------------|------------------|
| 1. $f(\mathbf{x}^*) > f(\mathbf{x}), \forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$    | $\implies$ | Strict Local Max |
| 2. $f(\mathbf{x}^*) \geq f(\mathbf{x}), \forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$ | $\implies$ | Local Max        |
| 3. $f(\mathbf{x}^*) < f(\mathbf{x}), \forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$    | $\implies$ | Strict Local Min |
| 4. $f(\mathbf{x}^*) \leq f(\mathbf{x}), \forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$ | $\implies$ | Local Min        |

$x^*$  is a *local max* if there are no nearby points at which  $f$  takes a larger value.

### 1.5.6 First Order Conditions

When we examined functions of one variable  $x$ , we found critical points by taking the first derivative, setting it to zero, and solving for  $x$ . For functions of  $n$  variables, the critical points are found in much the same way, except now we set the partial derivatives equal to zero.<sup>8</sup>

- **Gradient** ( $\nabla f(\mathbf{x})$ ): Given a function  $f(\mathbf{x})$  in  $n$  variables, the gradient  $\nabla f(\mathbf{x})$  is a column vector, where the  $i$ th element is the partial derivative of  $f(\mathbf{x})$  with respect to  $x_i$ :

$$\nabla f(\mathbf{x}) = \begin{pmatrix} \frac{\partial f(\mathbf{x})}{\partial x_1} \\ \frac{\partial f(\mathbf{x})}{\partial x_2} \\ \vdots \\ \frac{\partial f(\mathbf{x})}{\partial x_n} \end{pmatrix}$$

- **Critical Point:**  $\mathbf{x}^*$  is a critical point iff  $\nabla f(\mathbf{x}^*) = 0$ . If the partial derivative of  $f(\mathbf{x})$  with respect to  $x_i$  is 0, then  $\mathbf{x}^*$  is a critical point. To solve for  $\mathbf{x}^*$ , find the gradient, set each element equal to 0, and solve the system of equations.

$$\mathbf{x}^* = \begin{pmatrix} x_1^* \\ x_2^* \\ \vdots \\ x_n^* \end{pmatrix}$$

<sup>8</sup>We will only consider critical points on the interior of a function's domain.

Example: Given a function  $f(\mathbf{x}) = (x_1 - 1)^2 + x_2^2 + 1$ , find the:

1. Gradient  $\nabla f(\mathbf{x}) =$

2. Critical Point  $x^* =$

### 1.5.7 Second Order Conditions

When we found a critical point for a function of one variable, we used the second derivative as an indicator of the curvature at the point in order to determine whether the point was a min, max, or saddle (second derivative test of concavity). For functions of  $n$  variables, we use *second order partial derivatives* as an indicator of curvature.

- **Hessian ( $\mathbf{H}(\mathbf{x})$ ):** Given a function  $f(\mathbf{x})$  in  $n$  variables, the hessian  $\mathbf{H}(\mathbf{x})$  is an  $n \times n$  matrix, where the  $(i, j)$ th element is the second order partial derivative of  $f(\mathbf{x})$  with respect to  $x_i$  and  $x_j$ :

$$\mathbf{H}(\mathbf{x}) = \begin{pmatrix} \frac{\partial^2 f(\mathbf{x})}{\partial x_1^2} & \frac{\partial^2 f(\mathbf{x})}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f(\mathbf{x})}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f(\mathbf{x})}{\partial x_2 \partial x_1} & \frac{\partial^2 f(\mathbf{x})}{\partial x_2^2} & \cdots & \frac{\partial^2 f(\mathbf{x})}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f(\mathbf{x})}{\partial x_n \partial x_1} & \frac{\partial^2 f(\mathbf{x})}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f(\mathbf{x})}{\partial x_n^2} \end{pmatrix}$$

Note that the hessian will be a symmetric matrix because  $\frac{\partial f(\mathbf{x})}{\partial x_1 \partial x_2} = \frac{\partial f(\mathbf{x})}{\partial x_2 \partial x_1}$ .

Also note that given that  $f(\mathbf{x})$  is of quadratic form, each element of the hessian will be a constant.

- **Second Order Conditions:**

Given a function  $f(\mathbf{x})$  and a point  $\mathbf{x}^*$  such that  $\nabla f(\mathbf{x}^*) = 0$ ,

1.  $\mathbf{H}(\mathbf{x}^*)$  Positive Definite  $\implies$  Strict Local Min
2.  $\mathbf{H}(\mathbf{x}^*)$  Positive Semidefinite  $\implies$  Local Min  
 $\forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$
3.  $\mathbf{H}(\mathbf{x}^*)$  Negative Definite  $\implies$  Strict Local Max
4.  $\mathbf{H}(\mathbf{x}^*)$  Negative Semidefinite  $\implies$  Local Max  
 $\forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$
5.  $\mathbf{H}(\mathbf{x}^*)$  Indefinite  $\implies$  Saddle Point

Example: We found that the only critical point of  $f(\mathbf{x}) = (x_1 - 1)^2 + x_2^2 + 1$  is at  $\mathbf{x}^* = (1, 0)$ . Is it a min, max, or saddle point?

1. Hessian  $\mathbf{H}(\mathbf{x}) =$
2. Leading principal minors of  $\mathbf{H}(\mathbf{x}) =$
3. Definiteness?
4. Maxima, Minima, or Saddle Point?
5. Alternate check of definiteness. Is  $\mathbf{H}(\mathbf{x}^*) \geq \leq \mathbf{0} \quad \forall \quad \mathbf{x} \neq \mathbf{0}$ ?

### 1.5.8 Definiteness and Concavity

Although definiteness helps us to understand the curvature of an n-dimensional function, it does not necessarily tell us whether the function is globally concave or convex.

We need to know whether a function is globally concave or convex to determine whether a critical point is a global min or max.

- **Testing for Global Concavity:** We can use the definiteness of the Hessian to determine whether a function is globally concave or convex:
  1.  $\mathbf{H}(\mathbf{x})$  Positive Semidefinite  $\forall \mathbf{x} \quad \implies \quad$  Globally Convex
  2.  $\mathbf{H}(\mathbf{x})$  Negative Semidefinite  $\forall \mathbf{x} \quad \implies \quad$  Globally Concave

Notice that the definiteness conditions must be satisfied over the entire domain.

### 1.5.9 Global Maxima and Minima

- **Global Max/Min Conditions:** Given a function  $f(\mathbf{x})$  and a point  $\mathbf{x}^*$  such that  $\nabla f(\mathbf{x}^*) = 0$ ,
  1.  $f(\mathbf{x})$  Globally Convex  $\implies \quad$  Global Min
  2.  $f(\mathbf{x})$  Globally Concave  $\implies \quad$  Global Max

Note that showing that  $\mathbf{H}(\mathbf{x}^*)$  is negative semidefinite is not enough to guarantee  $\mathbf{x}^*$  is a local max. However, showing that  $\mathbf{H}(\mathbf{x})$  is negative semidefinite for all  $\mathbf{x}$  guarantees that  $x^*$  is a global max. (The same goes for positive semidefinite and minima.)

Example: Take  $f_1(x) = x^4$  and  $f_2(x) = -x^4$ . Both have  $x = 0$  as a critical point. Unfortunately,  $f_1''(0) = 0$  and  $f_2''(0) = 0$ , so we can't tell whether  $x = 0$  is a min or max for either. However,  $f_1''(x) = 12x^2$  and  $f_2''(x) = -12x^2$ . For all  $x$ ,  $f_1''(x) \geq 0$  and  $f_2''(x) \leq 0$  — i.e.,  $f_1(x)$  is globally convex and  $f_2(x)$  is globally concave. So  $x = 0$  is a global min of  $f_1(x)$  and a global max of  $f_2(x)$ .

### 1.5.10 Example

Given  $f(\mathbf{x}) = x_1^3 - x_2^3 + 9x_1x_2$ , find any maxima or minima.

1. First order conditions.

(a) Gradient  $\nabla f(\mathbf{x}) =$

(b) Critical Points  $\mathbf{x}^* =$

2. Second order conditions.

(a) Hessian  $\mathbf{H}(\mathbf{x}) =$

(b) Hessian  $\mathbf{H}(\mathbf{x}_1^*) =$

(c) Leading principal minors of  $\mathbf{H}(\mathbf{x}_1^*) =$

(d) Definiteness of  $\mathbf{H}(\mathbf{x}_1^*)?$

(e) Maxima, Minima, or Saddle Point for  $\mathbf{x}_1^*$ ?

(f) Hessian  $\mathbf{H}(\mathbf{x}_2^*) =$

- (g) Leading principal minors of  $\mathbf{H}(\mathbf{x}_2^*) =$
- (h) Definiteness of  $\mathbf{H}(\mathbf{x}_2^*)$ ?
- (i) Maxima, Minima, or Saddle Point for  $\mathbf{x}_2^*$ ?
3. Global concavity/convexity.
- (a) Is  $f(x)$  globally concave/convex?
- (b) Are any  $\mathbf{x}^*$  global minima or maxima?

### 1.5.11 Taylor Series Approximation

- **Taylor series** (also known as the delta method) are used commonly to represent functions as infinite series of the function's derivatives at some point  $a$ . For example, Taylor series are very helpful in representing *nonlinear* functions as linear functions. One can thus *approximate* functions by using lower-order, finite series known as **Taylor polynomials**. If  $a = 0$ , the series is called a **Maclaurin series**.
- Specifically, a Taylor series of a real or complex function  $f(x)$  that is infinitely differentiable in the neighborhood of point  $a$  is:

$$\begin{aligned} f(x) &= f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \dots \\ &= \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}(x-a)^n \end{aligned}$$

- **Taylor Approximation:** We can often approximate the curvature of a function  $f(x)$  at point  $a$  using a 2nd order Taylor polynomial around point  $a$ :

$$f(x) = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + R_2$$

$R_2$  is the Lagrange remainder and often treated as negligible, giving us:

$$f(x) \approx f(a) + f'(a)(x-a) + \frac{f''(a)}{2}(x-a)^2$$

Taylor series expansion is easily generalized to multiple dimensions.

- **Curvature and The Taylor Polynomial as a Quadratic Form:** The Hessian is used in a Taylor polynomial approximation to  $f(\mathbf{x})$  and provides information about the curvature of  $f(\mathbf{x})$  at  $\mathbf{x}$  — e.g., which tells us whether a critical point  $\mathbf{x}^*$  is a min, max, or saddle point.

1. The second order Taylor polynomial about the critical point  $\mathbf{x}^*$  is

$$f(\mathbf{x}^* + \mathbf{h}) = f(\mathbf{x}^*) + \nabla f(\mathbf{x}^*)\mathbf{h} + \frac{1}{2}\mathbf{h}^T\mathbf{H}(\mathbf{x}^*)\mathbf{h} + \mathbf{R}(\mathbf{h})$$

2. Since we're looking at a critical point,  $\nabla f(\mathbf{x}^*) = 0$ ; and for small  $\mathbf{h}$ ,  $\mathbf{R}(\mathbf{h})$  is negligible. Rearranging, we get

$$f(\mathbf{x}^* + \mathbf{h}) - f(\mathbf{x}^*) \approx \frac{1}{2}\mathbf{h}^T\mathbf{H}(\mathbf{x}^*)\mathbf{h}$$

3. The RHS is a quadratic form and we can determine the definiteness of  $\mathbf{H}(\mathbf{x}^*)$ .

- (a) If  $\mathbf{H}(\mathbf{x}^*)$  is positive definite, then the RHS is positive for all small  $\mathbf{h}$ :

$$f(\mathbf{x}^* + \mathbf{h}) - f(\mathbf{x}^*) > 0 \quad f(\mathbf{x}^* + \mathbf{h}) > f(\mathbf{x}^*)$$

i.e.,  $f(\mathbf{x}^*) < f(\mathbf{x})$ ,  $\forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$ , so  $\mathbf{x}^*$  is a strict local min.

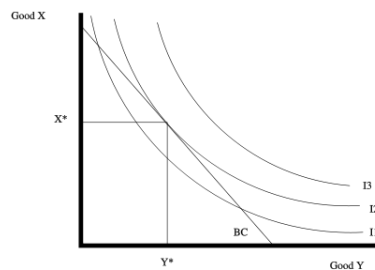
- (b) Conversely, if  $\mathbf{H}(\mathbf{x}^*)$  is negative definite, then the RHS is negative for all small  $\mathbf{h}$ :

$$f(\mathbf{x}^* + \mathbf{h}) - f(\mathbf{x}^*) < 0 \quad f(\mathbf{x}^* + \mathbf{h}) < f(\mathbf{x}^*)$$

i.e.,  $f(\mathbf{x}^*) > f(\mathbf{x})$ ,  $\forall \mathbf{x} \in B(\mathbf{x}^*, \epsilon)$ , so  $\mathbf{x}^*$  is a strict local max.

### 1.5.12 Constrained Optimization

We have already looked at optimizing a function in one or more dimensions over the whole domain of the function. Often, however, we want to find the maximum or minimum of a function over some restricted part of its domain. One example of a constrained maximization problem would be maximizing utility subject to a budget constraint.



- **Types of Constraints:** For a function  $f(x_1, \dots, x_n)$ , there are two types of constraints that can be imposed:

1. **Equality constraints:** constraints of the form  $c(x_1, \dots, x_n) = r$ . Budget constraints are the classic example of equality constraints in social science.
2. **Inequality constraints:** constraints of the form  $c(x_1, \dots, x_n) \leq r$ . These might arise from non-negativity constraints or other threshold effects.

In any constrained optimization problem, the constrained maximum will always be less than or equal to the unconstrained maximum. If the constrained maximum is less than the unconstrained maximum, then the constraint is binding. Essentially, this means that you can treat your constraint as an equality constraint rather than an inequality constraint.

Example: The budget constraint binds when you spend your entire budget. This generally happens because we believe that utility is strictly increasing in consumption, i.e. you always want more so you spend everything you have.

Any number of constraints can be placed on an optimization problem. When working with multiple constraints, always make sure that the set of constraints are not pathological; it must be possible for all of the constraints to be satisfied simultaneously.

- **Set-up for Constrained Optimization:**

$$\max_{x_1, x_2} f(x_1, x_2) \text{ s.t. } c(x_1, x_2)$$

$$\min_{x_1, x_2} f(x_1, x_2) \text{ s.t. } c(x_1, x_2)$$

This tells us to maximize/minimize our function,  $f(x_1, x_2)$ , with respect to the choice variables,  $x_1, x_2$ , subject to the constraint.

Example:

$$\max_{x_1, x_2} f(x_1, x_2) = -(x_1^2 + 2x_2^2) \text{ s.t. } x_1 + x_2 = 4$$

It is easy to see that the *unconstrained* maximum occurs at  $(x_1, x_2) = (0, 0)$ , but that does not satisfy the constraint. How should we proceed?

### 1.5.13 Equality Constraints

Equality constraints are the easiest to deal with because we know that the maximum or minimum has to lie on the (intersection of the) constraint(s).

The trick is to change the problem from a constrained optimization problem in  $n$  variables to an unconstrained optimization problem in  $n + k$  variables, adding *one* variable for *each* equality constraint. We do this using a Lagrangian multiplier.

- **Lagrangian function:** The Lagrangian function allows us to combine the function we want to optimize and the constraint function into a single function. Once we have this single function, we can proceed as if this were an *unconstrained* optimization problem.

For each constraint, we must include a **Lagrange multiplier** ( $\lambda_i$ ) as an additional variable in the analysis. These terms are the link between the constraint and the Lagrangian function.

Given a *two dimensional* set-up:

$$\max_{x_1, x_2} / \min_{x_1, x_2} f(x_1, x_2) \text{ s.t. } c(x_1, x_2) = a$$

We define the Lagrangian function  $L(x_1, x_2, \lambda_1)$  as follows:

$$L(x_1, x_2, \lambda_1) = f(x_1, x_2) - \lambda_1(c(x_1, x_2) - a)$$

More generally, in  $n$  dimensions:

$$L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k) = f(x_1, \dots, x_n) - \sum_{i=1}^k \lambda_i(c_i(x_1, \dots, x_n) - r_i)$$

### Getting the sign right:

Note that above we subtract the Lagrangian term *and* we subtract the constraint constant from the constraint function.

Occasionally, you may see the following alternative form of the Lagrangian, which is *equivalent*:

$$L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k) = f(x_1, \dots, x_n) + \sum_{i=1}^k \lambda_i(r_i - c_i(x_1, \dots, x_n))$$

Here we add the Lagrangian term *and* we subtract the constraining function from the constraint constant.

- **Using the Lagrangian to Find the Critical Points:** To find the critical points, we take the partial derivatives of Lagrangian function,  $L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k)$ , with respect to each of its variables (all choice variables  $\mathbf{x}$  *and* all Lagrangian multipliers  $\lambda$ ). At a critical point, *each* of these partial derivatives must be equal to zero, so we obtain a system of  $n+k$  equations in  $n+k$  unknowns:

$$\begin{aligned} \frac{\partial L}{\partial x_1} &= \frac{\partial f}{\partial x_1} - \sum_{i=1}^k \lambda_i \frac{\partial c_i}{\partial x_1} = 0 \\ &\vdots = \vdots \\ \frac{\partial L}{\partial x_n} &= \frac{\partial f}{\partial x_n} - \sum_{i=1}^k \lambda_i \frac{\partial c_i}{\partial x_n} = 0 \\ \frac{\partial L}{\partial \lambda_1} &= c_1(x_1, \dots, x_n) - r_1 = 0 \\ &\vdots = \vdots \\ \frac{\partial L}{\partial \lambda_k} &= c_k(x_1, \dots, x_n) - r_k = 0 \end{aligned}$$

We can then solve this system of equations, because there are  $n+k$  equations and  $n+k$  unknowns, to calculate the critical point  $(x_1^*, \dots, x_n^*, \lambda_1^*, \dots, \lambda_k^*)$ .

- **Second-order Conditions and Unconstrained Optimization:** There may be more than one critical point, i.e. we need to verify that the critical point we find is a maximum/minimum. Similar to unconstrained optimization, we can do this by checking the second-order conditions.

Example:

$$\max_{x_1, x_2} f(x) = -(x_1^2 + 2x_2^2) \text{ s.t. } x_1 + x_2 = 4$$

1. Begin by writing the Lagrangian:

$$L(x_1, x_2, \lambda) =$$

2. Take the partial derivatives and set equal to zero:

$$\begin{aligned} \frac{\partial L}{\partial x_1} &= &= 0 \\ \frac{\partial L}{\partial x_2} &= &= 0 \\ \frac{\partial L}{\partial \lambda} &= &= 0 \end{aligned}$$

3. Solve the system of equations:

Notice that when we take the partial derivative of  $L$  with respect to the Lagrangian multiplier and set it equal to 0, we return exactly our constraint! This is why signs matter.

### 1.5.14 Inequality Constraints

Inequality constraints define the boundary of a region over which we seek to optimize the function. This makes inequality constraints more challenging because we do not know if the maximum/minimum lies along one of the constraints (the constraint binds) or in the interior of the region.

We must introduce more variables in order to turn the problem into an unconstrained optimization.

- **Slack:** For *each* inequality constraint  $c_i(x_1, \dots, x_n) \leq a_i$ , we define a slack variable  $s_i^2$  for which the expression  $c_i(x_1, \dots, x_n) \leq a_i - s_i^2$  would hold with equality. These slack variables capture how close the constraint comes to binding. We use  $s^2$  rather than  $s$  to ensure that the slack is positive.

Slack is just a way to transform our constraints.

Given a *two-dimensional* set-up and these edited constraints:

$$\max_{x_1, x_2} / \min_{x_1, x_2} f(x_1, x_2) \text{ s.t. } c(x_1, x_2) \leq a_1$$

Adding in Slack:

$$\max_{x_1, x_2} / \min_{x_1, x_2} f(x_1, x_2) \text{ s.t. } c(x_1, x_2) \leq a_1 - s_1^2$$

We define the Lagrangian function  $L(x_1, x_2, \lambda_1, s_1)$  as follows:

$$L(x_1, x_2, \lambda_1, s_1) = f(x_1, x_2) - \lambda_1(c(x_1, x_2) + s_1^2 - a_1)$$

More generally, in  $n$  dimensions:

$$L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k, s_1, \dots, s_k) = f(x_1, \dots, x_n) - \sum_{i=1}^k \lambda_i(c_i(x_1, \dots, x_n) + s_i^2 - a_i)$$

- **Finding the Critical Points:** To find the critical points, we take the partial derivatives of the lagrangian function,  $L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k, s_1, \dots, s_k)$ , with respect to each of its variables (all choice variables  $x$ , all lagrangian multipliers  $\lambda$ , and all slack variables  $s$ ). At a critical point, *each* of these partial derivatives must be equal to zero, so we obtain a system of  $n + 2k$  equations in  $n + 2k$  unknowns:

$$\begin{aligned} \frac{\partial L}{\partial x_1} &= \frac{\partial f}{\partial x_1} - \sum_{i=1}^k \lambda_i \frac{\partial c_i}{\partial x_1} = 0 \\ &\vdots = \vdots \\ \frac{\partial L}{\partial x_n} &= \frac{\partial f}{\partial x_n} - \sum_{i=1}^k \lambda_i \frac{\partial c_i}{\partial x_n} = 0 \\ \frac{\partial L}{\partial \lambda_1} &= c_1(x_1, \dots, x_n) + s_1^2 - b_1 = 0 \\ &\vdots = \vdots \\ \frac{\partial L}{\partial \lambda_k} &= c_k(x_1, \dots, x_n) + s_k^2 - b_k = 0 \\ &\frac{\partial L}{\partial s_1} = 2s_1\lambda_1 = 0 \\ &\vdots = \vdots \\ &\frac{\partial L}{\partial s_k} = 2s_k\lambda_k = 0 \end{aligned}$$

- **Complementary slackness conditions:** The last set of first order conditions of the form  $2s_i\lambda_i = 0$  (the partials taken with respect to the slack variables) are known as complementary slackness conditions. These conditions can be satisfied one of three ways:

1.  $\lambda_i = 0$  and  $s_i \neq 0$ : This implies that the slack is positive and thus *the constraint does not bind*.
2.  $\lambda_i \neq 0$  and  $s_i = 0$ : This implies that there is no slack in the constraint and *the constraint does bind*.

3.  $\lambda_i = 0$  and  $s_i = 0$ : In this case, there is no slack but the *constraint binds trivially*, without changing the optimum.

Example: Find the critical points for the following constrained optimization:

$$\max_{x_1, x_2} f(x) = -(x_1^2 + 2x_2^2) \text{ s.t. } x_1 + x_2 \leq 4$$

1. Rewrite with the slack variables:

$$\max_{x_1, x_2} f(x) = -(x_1^2 + 2x_2^2) \text{ s.t. } x_1 + x_2 \leq 4 - s_1^2$$

2. Write the Lagrangian:

$$L(x_1, x_2, \lambda_1, s_1) = -(x_1^2 + 2x_2^2) - \lambda_1(x_1 + x_2 + s_1^2 - 4)$$

3. Take the partial derivatives and set equal to 0:

$$\begin{aligned} \frac{\partial L}{\partial x_1} &= -2x_1 - \lambda_1 = 0 \\ \frac{\partial L}{\partial x_2} &= -4x_2 - \lambda_1 = 0 \\ \frac{\partial L}{\partial \lambda_1} &= -(x_1 + x_2 + s_1^2 - 4) = 0 \\ \frac{\partial L}{\partial s_1} &= -2s_1\lambda_1 = 0 \end{aligned}$$

4. Consider all ways that the complementary slackness conditions are solved:

Hypothesis	$s_1$	$\lambda_1$	$x_1$	$x_2$	$f(x_1, x_2)$
$s_1 = 0 \ \lambda_1 = 0$	No solution				
$s_1 \neq 0 \ \lambda_1 = 0$	2	0	0	0	0
$s_1 = 0 \ \lambda_1 \neq 0$	0	$-\frac{16}{3}$	$\frac{8}{3}$	$\frac{4}{3}$	$-\frac{32}{3}$
$s_1 \neq 0 \ \lambda_1 \neq 0$	No solution				

This shows that there are two critical points:  $(0, 0)$  and  $(\frac{8}{3}, \frac{4}{3})$ .

5. Find maximum: Looking at the values of  $f(x_1, x_2)$  at the critical points, we see that  $f(x_1, x_2)$  is maximized at  $x_1^* = 0$  and  $x_2^* = 0$ .

Example: Find the critical points for the following constrained optimization:

$$\max_{x_1, x_2} f(x) = -(x_1^2 + 2x_2^2) \text{ s.t. } \begin{aligned} x_1 + x_2 &\leq 4 \\ x_1 &\geq 0 \\ x_2 &\geq 0 \end{aligned}$$

1. Rewrite with the slack variables:

2. Write the Lagrangian:
  
3. Take the partial derivatives and set equal to zero:

4. Consider all ways that the complementary slackness conditions are solved:

Hypothesis	$s_1$	$s_2$	$s_3$	$\lambda_1$	$\lambda_2$	$\lambda_3$	$x_1$	$x_2$	$f(x_1, x_2)$
$s_1 = s_2 = s_3 = 0$									
$s_1 \neq 0, s_2 = s_3 = 0$									
$s_2 \neq 0, s_1 = s_3 = 0$									
$s_3 \neq 0, s_1 = s_2 = 0$									
$s_1 \neq 0, s_2 \neq 0, s_3 = 0$									
$s_1 \neq 0, s_3 \neq 0, s_2 = 0$									
$s_2 \neq 0, s_3 \neq 0, s_1 = 0$									
$s_1 \neq 0, s_2 \neq 0, s_3 \neq 0$									

5. Find maximum:

### 1.5.15 Kuhn-Tucker Conditions

As you can see, this can be a pain. When dealing explicitly with *non-negativity constraints*, this process is simplified by using the Kuhn-Tucker method.

- **Kuhn-Tucker conditions:** Because the problem of maximizing a function subject to inequality and non-negativity constraints arises frequently in economics, the Kuhn-Tucker approach provides a method that often makes it easier to both calculate the critical points and identify points that are (local) maxima.

Given a *two-dimensional set-up*:

$$\max_{x_1, x_2} / \min_{x_1, x_2} f(x_1, x_2) \text{ s.t. } \begin{cases} c(x_1, x_2) \leq a_1 \\ x_1 \geq 0 \\ gx_2 \geq 0 \end{cases}$$

We define the Lagrangian function  $L(x_1, x_2, \lambda_1)$  the same as if we did not have the non-negativity constraints:

$$L(x_1, x_2, \lambda_1) = f(x_1, x_2) - \lambda_1(c(x_1, x_2) - a_1)$$

More generally, in  $n$  dimensions:

$$L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k) = f(x_1, \dots, x_n) - \sum_{i=1}^k \lambda_i(c_i(x_1, \dots, x_n) - a_i)$$

- **Kuhn-Tucker and Complementary Slackness Conditions:** To find the critical points, we first calculate the **Kuhn-Tucker conditions** by taking the partial derivatives of the Lagrangian function,  $L(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k)$ , with respect to each of its variables (all choice variables  $x$  and all Lagrangian multipliers  $\lambda$ ) and we calculate the **complementary slackness conditions** by multiplying each partial derivative by its respective variable and include **non-negativity conditions** for all variables (choice variables  $x$  and Lagrangian multipliers  $\lambda$ ).

### Kuhn-Tucker Conditions

$$\begin{aligned} \frac{\partial L}{\partial x_1} &\leq 0, & \dots, & & \frac{\partial L}{\partial x_n} &\leq 0 \\ \frac{\partial L}{\partial \lambda_1} &\geq 0, & \dots, & & \frac{\partial L}{\partial \lambda_m} &\geq 0 \end{aligned}$$

### Complementary Slackness Conditions

$$\begin{aligned} x_1 \frac{\partial L}{\partial x_1} &= 0, & \dots, & & x_n \frac{\partial L}{\partial x_n} &= 0 \\ \lambda_1 \frac{\partial L}{\partial \lambda_1} &= 0, & \dots, & & \lambda_m \frac{\partial L}{\partial \lambda_m} &= 0 \end{aligned}$$

### Non-negativity Conditions

$$\begin{aligned} x_1 &\geq 0 & \dots & & x_n &\geq 0 \\ \lambda_1 &\geq 0 & \dots & & \lambda_m &\geq 0 \end{aligned}$$

Note that some of these conditions are set equal to 0, while others are set as inequalities!

Note also that to minimize the function  $f(x_1, \dots, x_n)$ , the simplest thing to do is maximize the function  $-f(x_1, \dots, x_n)$ ; all of the conditions remain the same after reformulating as a maximization problem.

There are additional assumptions (notably,  $f(x)$  is quasi-concave and the constraints are convex) that are sufficient to ensure that a point satisfying the Kuhn-Tucker conditions is a global max; if these assumptions do not hold, you may have to check more than one point.

- **Finding the Critical Points with Kuhn-Tucker Conditions:** Given the above conditions, to find the critical points we solve the above system of equations. To do so, we must check *all* border and interior solutions to see if they satisfy the above conditions.

In a two-dimensional set-up, this means we must check the following cases:

- |                              |                   |
|------------------------------|-------------------|
| (1) $x_1 = 0, x_2 = 0$       | Border Solution   |
| (2) $x_1 = 0, x_2 \neq 0$    | Border Solution   |
| (3) $x_1 \neq 0, x_2 = 0$    | Border Solution   |
| (4) $x_1 \neq 0, x_2 \neq 0$ | Interior Solution |

Example:

$$\max_{x_1, x_2} f(x) = -(x_1^2 + 2x_2^2) \text{ s.t. } \begin{array}{l} x_1 + x_2 \leq 4 \\ x_1 \geq 0 \\ x_2 \geq 0 \end{array}$$

1. Write the Lagrangian:

$$L(x_1, x_2, \lambda) = -(x_1^2 + 2x_2^2) - \lambda(x_1 + x_2 - 4)$$

2. Find the First Order Conditions:  
Kuhn-Tucker Conditions

$$\begin{aligned} \frac{\partial L}{\partial x_1} &= -2x_1 - \lambda \leq 0 \\ \frac{\partial L}{\partial x_2} &= -4x_2 - \lambda \leq 0 \\ \frac{\partial L}{\partial \lambda} &= -(x_1 + x_2 - 4) \geq 0 \end{aligned}$$

Complementary Slackness Conditions

$$\begin{aligned} x_1 \frac{\partial L}{\partial x_1} &= x_1(-2x_1 - \lambda) = 0 \\ x_2 \frac{\partial L}{\partial x_2} &= x_2(-4x_2 - \lambda) = 0 \\ \lambda \frac{\partial L}{\partial \lambda} &= -\lambda(x_1 + x_2 - 4) = 0 \end{aligned}$$

Non-negativity Conditions

$$\begin{aligned} x_1 &\geq 0 \\ x_2 &\geq 0 \\ \lambda &\geq 0 \end{aligned}$$

3. Consider all border and interior cases:

Hypothesis	$\lambda$	$x_1$	$x_2$	$f(x_1, x_2)$
$x_1 = 0, x_2 = 0$	0	0	0	0
$x_1 = 0, x_2 \neq 0$	-16	0	4	-32
$x_1 \neq 0, x_2 = 0$	-8	4	0	-16
$x_1 \neq 0, x_2 \neq 0$	$-\frac{16}{3}$	$\frac{8}{3}$	$\frac{4}{3}$	$-\frac{32}{3}$

4. Find Maximum:

Three of the critical points violate the requirement that  $\lambda \geq 0$ , so the point  $(0, 0, 0)$  is the maximum.



4. Find Maximum:

## 1.6 Probability I: Probability Theory

### Today's Topics:

Counting rules; Sets; Probability; Conditional Probability and Bayes' Rule; Independence

#### 1.6.1 Counting rules

- **Fundamental Theorem of Counting:** If an object has  $j$  different characteristics and each characteristic has  $n_j$  ways of being expressed, then there are  $\prod_{i=1}^j n_j$  possible unique objects.

Example: Cards can be either red or black and can take on any of 13 values.  
 $j =$                        $n_{color} =$                        $n_{number} =$                        $\#$  Outcomes =

We often need to count the number of ways to choose a *subset* from some set of possibilities. The number of outcomes depends on two characteristics of the process: does the *order* matter and is *replacement* allowed?

- **Sampling Table:** If there are  $n$  objects and we select  $k < n$  of them, how many different outcomes are possible?

**Sampling Table**

	Order Matters	Order Doesn't Matter
<b>With Replacement</b>	$n^k$	$\binom{n+k-1}{k}$
<b>Without Replacement</b>	$\frac{n!}{(n-k)!}$	$\binom{n}{k}$

Where  $\binom{x}{y} = \frac{x!}{(x-y)!y!}$  and  $0! = 1$

Example: There are five balls numbered from 1 through 5 in a jar. Three balls are chosen. How many possible choices are there?

1. Ordered, with replacement =
2. Ordered, without replacement =
3. Unordered, with replacement =
4. Unordered, without replacement =

Much of the material and examples for this lecture are taken from Gill (2006) *Essential Mathematics for Political and Social Research*, Wackerly, Mendenhall, & Scheaffer (1996) *Mathematical Statistics with Applications*, Degroot (1985) *Probability and Statistics*, Morrow (1994) *Game Theory for Political Scientists*, King (1989) *Unifying Political Methodology*, and Ross (1987) *Introduction to Probability and Statistics for Scientists and Engineers*.

### 1.6.2 Sets

- **Set:** A set is any well defined collection of elements. If  $x$  is an element of  $S$ ,  $x \in S$ .
- **Sample Space (S):** A set or collection of all possible outcomes from some process. Outcomes in the set can be discrete elements (countable) or points along a continuous interval (uncountable).

Examples:

1. Discrete: the numbers on a die, the number of possible wars that could occur each year, whether a vote cast is for a Republican or Democrat.
  2. Continuous: GNP, arms spending, age.
- **Event:** Any collection of possible outcomes of an experiment. Any subset of the full set of possibilities, including the full set itself. Event  $A \subset S$ .
  - **Empty Set:** a set with no elements.  $S = \{\emptyset\}$
  - **Set operations:**
    1. **Union:** The union of two sets  $A$  and  $B$ ,  $A \cup B$ , is the set containing all of the elements in  $A$  or  $B$ .  

$$A_1 \cup A_2 \cup \dots \cup A_n = \bigcup_{i=1}^n A_i$$
    2. **Intersection:** The intersection of sets  $A$  and  $B$ ,  $A \cap B$ , is the set containing all of the elements in both  $A$  and  $B$ .  

$$A_1 \cap A_2 \cap \dots \cap A_n = \bigcap_{i=1}^n A_i$$
    3. **Complement:** If set  $A$  is a subset of  $S$ , then the complement of  $A$ , denoted  $A^C$ , is the set containing all of the elements in  $S$  that are not in  $A$ .
  - Properties of set operations:
    1. **Commutative:**  $A \cup B = B \cup A$ ;  $A \cap B = B \cap A$
    2. **Associative:**  $A \cup (B \cup C) = (A \cup B) \cup C$ ;  $A \cap (B \cap C) = (A \cap B) \cap C$
    3. **Distributive:**  $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$ ;  $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$
    4. **de Morgan's laws:**  $(A \cup B)^C = A^C \cap B^C$ ;  $(A \cap B)^C = A^C \cup B^C$
  - **Disjointness:** Sets are disjoint when they do not intersect, such that  $A \cap B = \{\emptyset\}$ . A collection of sets is pairwise disjoint (**mutually exclusive**) if, for all  $i \neq j$ ,  $A_i \cap A_j = \{\emptyset\}$ . A collection of sets form a partition of set  $S$  if they are pairwise disjoint and they cover set  $S$ , such that  $\bigcup_{i=1}^k A_i = S$ .

### 1.6.3 Probability

- **Probability:** Many events or outcomes are random. In everyday speech, we say that we are *uncertain* about the outcome of random events. Probability is a formal model of uncertainty which provides a measure of uncertainty governed by a particular set of rules. A different model of uncertainty would, of course, have a different set of rules and measures. Our focus on probability is justified because it has proven to be a particularly useful model of uncertainty.

- **Probability Distribution Function (Pr(A))**: a mapping of each event in the sample space  $S$  to the real numbers that satisfy the following three axioms (also called Kolmogorov's Axioms).

**Axioms of Probability:** Define  $\Pr(A)$  as the probability of event  $A$  occurring in sample space  $S$ , such that:

1. For any event  $A$ ,  $\Pr(A) \geq 0$ .
2.  $\Pr(S) = 1$
3. For any sequence of *disjoint* (mutually exclusive) events  $A_1, A_2, \dots$  (of which there may be infinitely many),

$$\Pr\left(\bigcup_{i=1}^k A_i\right) = \sum_{i=1}^k \Pr(A_i)$$

- **Basic Rules of Probability:** Using these three axioms, we can define all of the common rules of probability.

1.  $\Pr(\emptyset) = 0$
  2. For any event  $A$ ,  $0 \leq \Pr(A) \leq 1$ .
  3.  $\Pr(A^C) = 1 - \Pr(A)$
  4. If  $A \subset B$  ( $A$  is a subset of  $B$ ), then  $\Pr(A) \leq \Pr(B)$ .
  5. For *any* two events  $A$  and  $B$ ,  $\Pr(A \cup B) = \Pr(A) + \Pr(B) - \Pr(A \cap B)$
  6. Boole's Inequality: For any sequence of  $n$  events (which need not be disjoint)  $A_1, A_2, \dots, A_n$ ,
- $$\Pr\left(\bigcup_{i=1}^n A_i\right) \leq \sum_{i=1}^n \Pr(A_i)$$

Examples: Let's assume we have an evenly-balanced, six-sided die. Then,

1. Sample space  $S =$
2.  $\Pr(1) = \dots = \Pr(6) =$
3.  $\Pr(\emptyset) = \Pr(7) =$
4.  $\Pr(\{1, 3, 5\}) =$
5.  $\Pr(\{1, 2\}^C) =$
6. Let  $A = \{1, 2, 3, 4, 5\} \subset S$ . Then  $\Pr(A) =$  <  $\Pr(S) =$  .
7. Let  $A = \{1, 2, 3\}$  and  $B = \{2, 4, 6\}$ . Then  
 $A \cup B =$   
 $A \cap B =$

$$\Pr(A \cup B) =$$

$$=$$

### 1.6.4 Conditional Probability and Bayes Law

- **Conditional Probability:** The conditional probability  $\Pr(A|B)$  of an event  $A$  is the probability of  $A$ , given that another event  $B$  has occurred. Conditional probability allows for the inclusion of other information into the calculation of the probability of an event. It is calculated as

$$\Pr(A|B) = \frac{\Pr(A \cap B)}{\Pr(B)}$$

Note that conditional probabilities are probabilities and must also follow the Kolmogorov axioms of probability.

Example: Assume  $A$  and  $B$  occur with the following frequencies:

	$A$	$A^C$
$B$	$n_{ab}$	$n_{a^c b}$
$B^C$	$n_{ab^c}$	$n_{(ab)^c}$

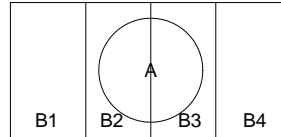
and let  $n_{ab} + n_{a^c b} + n_{ab^c} + n_{(ab)^c} = N$ . Then

1.  $\Pr(A) =$
2.  $\Pr(B) =$
3.  $\Pr(A \cap B) =$
4.  $\Pr(A|B) =$
5.  $\Pr(B|A) =$

Example: A six-sided die is rolled. What is the probability of a 1, given the outcome is an odd number?

- **Multiplicative Law of Probability:** The probability of the intersection of two events  $A$  and  $B$  is  $\Pr(A \cap B) = \Pr(A) \Pr(B|A) = \Pr(B) \Pr(A|B)$  which follows directly from the definition of conditional probability. More generally,  
 $P(A_1 \cap \dots \cap A_k) = P(A_k | A_{k-1} \cap \dots \cap A_1) \times P(A_{k-1} | A_{k-2} \cap \dots \cap A_1) \dots \times P(A_2 | A_1) \times P(A_1)$

- **Law of Total Probability:** Let  $S$  be the sample space of some experiment and let the disjoint  $k$  events  $B_1, \dots, B_k$  partition  $S$ , such that  $P(B_1 \cup \dots \cup B_k) = P(S) = 1$ . If  $A$  is some other event in  $S$ , then the events  $A \cap B_1, A \cap B_2, \dots, A \cap B_k$  will form a partition of  $A$  and we can write  $A$  as  $A = (A \cap B_1) \cup \dots \cup (A \cap B_k)$ .



Since the  $k$  events are disjoint,

$$\begin{aligned} \Pr(A) &= \sum_{i=1}^k \Pr(A \cap B_i) \\ &= \sum_{i=1}^k \Pr(B_i) \Pr(A|B_i) \end{aligned}$$

Sometimes it is easier to calculate these conditional probabilities and sum them than it is to calculate  $\Pr(A)$  directly.

- **Bayes Rule:** Assume that events  $B_1, \dots, B_k$  form a partition of the space  $S$ . Then by the Law of Total Probability

$$\Pr(B_j|A) = \frac{\Pr(A \cap B_j)}{\Pr(A)} = \frac{\Pr(B_j) \Pr(A|B_j)}{\sum_{i=1}^k \Pr(B_i) \Pr(A|B_i)}$$

If there are only two states of  $B$ , then this is just

$$\Pr(B_1|A) = \frac{\Pr(B_1) \Pr(A|B_1)}{\Pr(B_1) \Pr(A|B_1) + \Pr(B_2) \Pr(A|B_2)}$$

Bayes' rule determines the posterior probability of a state  $\Pr(B_j|A)$  by calculating the probability  $\Pr(A \cap B_j)$  that both the event  $A$  and the state  $B_j$  will occur and dividing it by the probability that the event will occur regardless of the state (by summing across all  $B_i$ ). The states could be something like Normal/Defective, Healthy/Diseased, Republican/Democrat/Independent, etc. The event on which one conditions could be something like a sampling from a batch of components, a test for a disease, or a question about a policy position.

- **Prior and Posterior Probabilities:** Above,  $\Pr(B_1)$  is often called the prior probability, since it's the probability of  $B_1$  before anything else is known.  $\Pr(B_1|A)$  is called the posterior probability, since it's the probability after other information is taken into account.



### 1.6.5 Independence

- **Independence:** If the occurrence or nonoccurrence of either events  $A$  and  $B$  have no effect on the occurrence or nonoccurrence of the other, then  $A$  and  $B$  are independent. If  $A$  and  $B$  are independent, then

1.  $\Pr(A|B) = \Pr(A)$
2.  $\Pr(B|A) = \Pr(B)$
3.  $\Pr(A \cap B) = \Pr(A) \Pr(B)$   
 $\Pr(\bigcap_{i=1}^k A_i) = \prod_{i=1}^k \Pr(A_i)$

Are mutually exclusive events independent of each other?

No. If  $A$  and  $B$  are mutually exclusive, then they cannot happen simultaneously. If we know that  $A$  occurred, then we know that  $B$  couldn't have occurred. Because of this,  $A$  and  $B$  aren't independent.

- **Pairwise Independence:** A set of more than two events  $A_1, A_2, \dots, A_k$  is pairwise independent if  $\Pr(A_i \cap A_j) = \Pr(A_i) \Pr(A_j)$ ,  $\forall i \neq j$ . Note that this does *not* necessarily imply independence.

- **Conditional Independence:** If  $A$  and  $B$  are independent once you know the occurrence of a third event  $C$ , then  $A$  and  $B$  are conditionally independent (conditional on  $C$ ):

1.  $\Pr(A|B \cap C) = \Pr(A|C)$
2.  $\Pr(B|A \cap C) = \Pr(B|C)$
3.  $\Pr(A \cap B|C) = \Pr(A|C) \Pr(B|C)$

## 1.7 Probability II: Random Variables

### Today's Topics:

Levels of Measurement; Random Variables; Discrete Distributions; Continuous Distributions; Expectation; Special Discrete Distributions; Special Continuous Distributions; Joint Distributions; Summarizing Observed Data

### 1.7.1 Levels of Measurement

In empirical research, data can be classified along several dimensions. We can look at the precision with which the underlying quantities are measured.

- **Nominal** (Categorical): *Discrete* data are nominal if there is no way to put the categories represented by the data into a meaningful order. Typically, this kind of data represents names (hence “nominal”) or attributes. Example: Republican or Democrat, Male or Female.
- **Ordinal**: *Discrete* data are ordinal if there is a logical order to the categories represented by the data, but there is no common scale for differences between adjacent categories. Example: Party identification, common survey responses.
- **Interval**: *Discrete or continuous* data are interval if there is an order to the values and there is a common scale, so that differences between two values have substantive meanings. Example: dates, temperature.
- **Ratio**: Discrete or continuous data are ratio if the data have the characteristics of interval data and zero is a meaningful quantity. This allows us to consider the ratio of two values as well as difference between them. Allows direct ratio comparison because of the meaningful baseline of 0. Example: quantities measured in dollars, crime rates.

### 1.7.2 Random Variables

- **Randomness** means that the outcome of some experiment is not deterministic, i.e. there is some probability ( $0 < P(A) < 1$ ) that the event will occur.
- **Random Variable**: A random variable is a real-valued function mapping the sample space  $S$  to the real line; it assigns a real number to every outcome  $s \in S$ . Random variables describe unobserved events. The **support** of a random variable is all values for which there is a positive probability of occurrence.

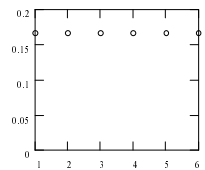
Example: Flip a fair coin 10 times. Count the number of heads.  
 What is the sample space?  
 What are other possible random variables?

### 1.7.3 Discrete Distributions

- **Discrete Random Variable:**  $Y$  is a discrete random variable if it can assume only a finite or countably infinite number of distinct values. Examples: number of wars per year, heads or tails.
- **Probability Mass Function** ( $p(y)$ ): For a discrete random variable  $Y$ , the probability mass function<sup>11</sup> (pmf),  $p(y) = \Pr(Y = y)$ , assigns probabilities to a countable number of distinct  $y$  values such that

1.  $0 \leq p(y) \leq 1$
2.  $\sum_y p(y) = 1$

Example: For a fair six-sided die, there is an equal probability of rolling any number. Since there are six sides, the probability mass function is then  $p(y) = 1/6$  for  $y = 1, \dots, 6$ , 0 otherwise.



- **Cumulative Density Function:** The cumulative density function<sup>12</sup>,  $F(y)$  or  $\Pr(Y \leq y)$ , is the probability that  $Y$  is less than or equal to some value  $y$ , or

$$\Pr(Y \leq y) = \sum_{i \leq y} p(i)$$

. Properties a CDF must satisfy:

1.  $F(y)$  is non-decreasing in  $y$ .
2.  $\lim_{y \rightarrow -\infty} F(y) = 0$  and  $\lim_{y \rightarrow \infty} F(y) = 1$
3.  $F(y)$  is right-continuous.

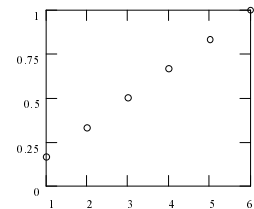
Note that  $P(Y > y) = 1 - P(Y \leq y)$ .

Example: For a fair die,

$$\Pr(Y \leq 1)$$

$$\Pr(Y \leq 3) =$$

$$\Pr(Y \leq 6) =$$



<sup>11</sup>Also referred to simply as the “probability distribution.”

<sup>12</sup>Also referred to simply as the “cumulative distribution.”

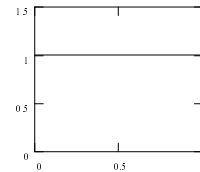
## 1.7.4 Continuous Distributions

- **Continuous Random Variable:**  $Y$  is a continuous random variable if there exists a nonnegative function  $f(y)$  defined for all real  $y \in (-\infty, \infty)$ , such that for any interval  $A$ ,  $\Pr(Y \in A) = \int_A f(y)dy$ . Examples: age, income, GNP, temperature.
- **Probability Density Function:** The function  $f$  above is called the probability density function (pdf) of  $Y$  and must satisfy

1.  $f(y) \geq 0$
2.  $\int_{-\infty}^{\infty} f(y)dy = 1$

Note also that  $\Pr(Y = y) = 0$  — i.e., the probability of any point  $y$  is zero.

Example:  $f(y) = 1, \quad 0 \leq y \leq 1$



- **Cumulative Density Function:** Because the probability that a continuous random variable will assume any particular value is zero, we can only make statements about the probability of a continuous random variable being within an interval. The cumulative distribution gives the probability that  $Y$  lies on the interval  $(-\infty, y)$  and is defined as

$$F(y) = \Pr(Y \leq y) = \int_{-\infty}^y f(s)ds$$

Note that  $F(y)$  has similar properties with continuous distributions as it does with discrete: non-decreasing, continuous (not just right-continuous), and  $\lim_{y \rightarrow -\infty} F(y) = 0$  and  $\lim_{y \rightarrow \infty} F(y) = 1$ .

We can also make statements about the probability of  $Y$  falling in an interval  $a \leq y \leq b$ .

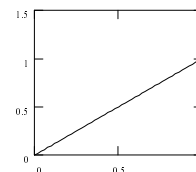
$$\Pr(a \leq y \leq b) = \int_a^b f(y)dy$$

- **Link between PDF and CDF:**  $f(y) = F'(y) = \frac{dF(y)}{dy}$

Example:  $f(y) = 1, \quad 0 < y < 1.$

$F(y) =$

$\Pr(.5 < y < .75) =$



### 1.7.5 Expectation

We often want to summarize some characteristics of the distribution of a random variable. The most important summary is the expectation (or expected value, or mean), in which the possible values of a random variable are weighted by their probabilities.

- **Expectation of a Discrete Random Variable:** The expected value of a discrete random variable  $Y$  is

$$E(Y) = \sum_y yP(Y = y) = \sum_y yp(y)$$

In words, it is the weighted average of all possible values of  $Y$ , weighted by the probability that  $y$  occurs. It is not necessarily the number we would expect  $Y$  to take on, but the average value of  $Y$  after a large number of repetitions of an experiment.

Example: For a fair die,  $E(Y) =$

- **Expectation of a Continuous Random Variable:** The expected value of a continuous random variable is similar in concept to that of the discrete random variable, except that instead of summing using probabilities as weights, we integrate using the density to weight. Hence, the expected value of the continuous variable  $Y$  is defined by

$$E(Y) = \int_y yf(y)dy$$

Example: Find  $E(Y)$  for  $f(y) = \frac{1}{1.5}$ ,  $0 < y < 1.5$ .

$$E(Y) = \int_0^{1.5} \frac{1}{1.5} y dy = \frac{1}{3} y^2 \Big|_0^{1.5} = .75$$

- **Expected Value of a Function:**

1. Discrete:  $E[g(Y)] = \sum_y g(y)p(y)$

2. Continuous:  $E[g(Y)] = \int_{-\infty}^{\infty} g(y)f(y)dy$

- Properties of Expected Values:

1.  $E(c) = c$

2.  $E[E[Y]] = E[Y]$

3.  $E[cg(Y)] = cE[g(Y)]$

4. Linearity:  $E[g(Y_1) + \dots + g(Y_n)] = E[g(Y_1)] + \dots + E[g(Y_n)]$ , *regardless* of independence

5.  $E[XY] = E[X]E[Y]$ , if  $X$  and  $Y$  are independent

- **Conditional Expectation:** With joint distributions, we are often interested in the expected value of a variable  $Y$  if we could hold the other variable  $X$  fixed. This is the conditional expectation of  $Y$  given  $X = x$ :

1.  $Y$  discrete:  $E(Y|X = x) = \sum_y y p_{Y|X}(y|x)$
2.  $Y$  continuous:  $E(Y|X = x) = \int_y y f_{Y|X}(y|x) dy$

The conditional expectation is often used for prediction when one knows the value of  $X$  but not  $Y$ ; the realized value of  $X$  contains information about the unknown  $Y$  so long as  $E(Y|X = x) \neq E(Y) \forall x$ .

- **Variance:** We can also look at other summaries of the distribution, which build on the idea of taking expectations. Variance tells us about the “spread” of the distribution; it is the expected value of the squared deviations from the mean of the distribution. The standard deviation is simply the square root of the variance.

1. Variance:  $\sigma^2 = \text{Var}(Y) = E[(Y - E(Y))^2] = E(Y^2) - [E(Y)]^2$
2. Standard Deviation:  $\sigma = \sqrt{\text{Var}(Y)}$

- **Covariance and Correlation:** The covariance measures the degree to which two random variables vary together; if the covariance is positive,  $X$  tends to be larger than its mean when  $Y$  is larger than its mean. The covariance of a variable with itself is the variance of that variable.

$$\text{Cov}(X, Y) = E[(X - E(X))(Y - E(Y))] = E(XY) - E(X)E(Y)$$

The correlation coefficient is the covariance divided by the standard deviations of  $X$  and  $Y$ . It is a unitless measure and always takes on values in the interval  $[-1, 1]$ .

$$\rho = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X)\text{Var}(Y)}} = \frac{\text{Cov}(X, Y)}{\text{SD}(X)\text{SD}(Y)}$$

- Properties of Variance and Covariance:

1.  $\text{Var}(c) = 0$
2.  $\text{Var}[cY] = c^2 \text{Var}[Y]$
3.  $\text{Cov}[Y, Y] = \text{Var}[Y]$
4.  $\text{Cov}[X, Y] = \text{Cov}[Y, X]$
5.  $\text{Cov}[aX, bY] = ab \text{Cov}[X, Y]$
6.  $\text{Cov}[X + a, Y] = \text{Cov}[X, Y]$
7.  $\text{Cov}[X + Z, Y + W] = \text{Cov}[X, Y] + \text{Cov}[X, W] + \text{Cov}[Z, Y] + \text{Cov}[Z, W]$
8.  $\text{Var}[X + Y] = \text{Var}[X] + \text{Var}[Y] + 2\text{Cov}[X, Y]$

### 1.7.6 Special Discrete Distributions

- **Binomial Distribution:**  $Y$  is distributed binomial if it represents the number of “successes” observed in  $n$  independent, identical “trials,” where the probability of success in any trial is  $p$  and the probability of failure is  $q = 1 - p$ .

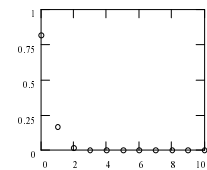
For any particular sequence of  $y$  successes and  $n - y$  failures, the probability of obtaining that sequence is  $p^y q^{n-y}$  (by the multiplicative law and independence). However, there are  $\binom{n}{y} = \frac{n!}{(n-y)!y!}$  ways of obtaining a sequence with  $y$  successes and  $n - y$  failures. So the binomial distribution is given by

$$p(y) = \binom{n}{y} p^y q^{n-y}, \quad y = 0, 1, 2, \dots, n$$

with mean  $\mu = E(Y) = np$  and variance  $\sigma^2 = V(Y) = npq$ .

Example: Republicans vote for Democrat-sponsored bills 2% of the time. What is the probability that out of 10 Republicans questioned, half voted for a particular Democrat-sponsored bill? What is the mean number of Republicans voting for Democrat-sponsored bills? The variance?

1.  $P(Y = 5) =$
2.  $E(Y) =$
3.  $V(Y) =$



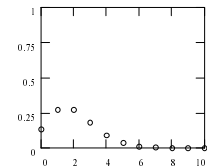
- **Poisson Distribution:** A random variable  $Y$  has a Poisson distribution if

$$p(y) = \frac{\lambda^y}{y!} e^{-\lambda}, \quad y = 0, 1, 2, \dots, \quad \lambda > 0$$

The Poisson has the unusual feature that its expectation equals its variance:  $E(Y) = V(Y) = \lambda$ . The Poisson distribution is often used to model rare event counts: counts of the number of events that occur during some unit of time.  $\lambda$  is often called the “arrival rate.”

Example: Border disputes occur between two countries at a rate of 2 per month. What is the probability of 0, 2, and less than 5 disputes occurring in a month?

1.  $P(Y = 0) =$
2.  $P(Y = 2) =$
3.  $\Pr(Y < 5) =$



### 1.7.7 Special Continuous Distributions

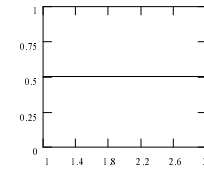
- **Uniform Distribution:** A random variable  $Y$  has a continuous uniform distribution on the interval  $(\alpha, \beta)$  if its density is given by

$$f(y) = \frac{1}{\beta - \alpha}, \quad \alpha \leq y \leq \beta$$

The mean and variance of  $Y$  are  $E(Y) = \frac{\alpha+\beta}{2}$  and  $V(Y) = \frac{(\beta-\alpha)^2}{12}$ .

Example:  $Y$  uniformly distributed over  $(1, 3)$ .

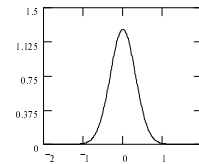
1.  $P(Y = 2) =$
2.  $f(2) =$
3.  $P(Y \leq 2) =$
4.  $P(Y > 2) =$



- **Normal Distribution:** A random variable  $Y$  is normally distributed with mean  $E(Y) = \mu$  and variance  $V(Y) = \sigma^2$  if its density is

$$f(y) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-\mu)^2}{2\sigma^2}}$$

Example:  $Y$  normally distributed with mean  $\mu = 0$  and variance  $\sigma^2 = .1$



### 1.7.8 Joint Distributions

Often, we are interested in two or more random variables defined on the same sample space. The distribution of these variables is called a joint distribution. Joint distributions can be made up of any combination of discrete and continuous random variables.

- **Joint Probability Distribution:** If both  $X$  and  $Y$  are random variable, their joint probability mass/density function assigns probabilities to each pair of outcomes

Discrete:  $p(x, y) = \Pr(X = x, Y = y)$

s.t.  $p(x, y) \in [0, 1]$  and  $\sum \sum p(x, y) = 1$

Continuous:  $f(x, y); \Pr((X, Y) \in A) = \iint_A f(x, y) dx dy$

s.t.  $f(x, y) \geq 0$  and  $\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) dx dy = 1$

If  $X$  and  $Y$  are independent, then  $P(X = x, Y = y) = P(X = x)P(Y = y)$  and  $f(x, y) = f(x)f(y)$

- **Marginal Probability Distribution:** probability distribution of only one of the two variables (ignoring information about the other variable), we can obtain the marginal distribution by summing/integrating across the variable that we don't care about:

Discrete:  $p_X(x) = \sum_i p(x, y_i)$

Continuous:  $f_X(x) = \int_{-\infty}^{\infty} f(x, y) dy$

- **Conditional Probability Distribution:** probability distribution for one variable, holding the other variable fixed. Recalling from the previous lecture that  $\Pr(A|B) = \frac{\Pr(A \cap B)}{\Pr(B)}$ , we can write the conditional distribution as

Discrete:  $p_{Y|X}(y|x) = \frac{p(x,y)}{p_X(x)}, \quad p_X(x) > 0$

Continuous:  $f_{Y|X}(y|x) = \frac{f(x,y)}{f_X(x)}, \quad f_X(x) > 0$

Example: Suppose we are interested in the outcomes of flipping a coin and rolling a 6-sided die at the same time. The sample space for this process contains 12 elements:

$$\{h1, h2, h3, h4, h5, h6, t1, t2, t3, t4, t5, t6\}$$

We can define two random variables  $X$  and  $Y$  such that  $X = 1$  if heads and  $X = 0$  if tails, while  $Y$  equals the number on the die. We can then make statements about the joint distribution of  $X$  and  $Y$ .

1.  $P(X = x) =$
2.  $P(Y = y) =$
3.  $P(X = x, Y = y) =$
4.  $P(X = x|Y = y) =$
5. Are  $X$  and  $Y$  independent?

### 1.7.9 Summarizing Observed Data

So far, we've talked about distributions in a theoretical sense, looking at different properties of random variables. We don't observe random variables; we observe realizations of the random variable.

- **Central tendency:** The central tendency describes the location of the "middle" of the observed data along some scale. There are several measures of central tendency.

1. **Sample mean:** This is the most common measure of central tendency, calculated by summing across the observations and dividing by the number of observations.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

The sample mean is an *estimate* of the expected value of a distribution.

2. **Sample median:** The median is the value of the "middle" observation. It is obtained by ordering  $n$  data points from smallest to largest and taking the value of the  $(n + 1)/2$ th observation (if  $n$  is odd) or the mean of the  $n/2$ th and  $(n + 1)/2$ th observations (if  $n$  is even).
3. **Sample mode:** The mode is the most frequently observed value in the data:

$$m_x = X_i : n(X_i) > n(X_j) \forall j \neq i$$

When the data are realizations of a continuous random variable, it often makes sense to group the data into bins, either by rounding or some other process, in order to get a reasonable estimate of the mode.

Example:

X	6	3	7	5	5	5	6	4	7	2
Y	1	2	1	2	2	1	2	0	2	0

- $\bar{x} =$   $\bar{y} =$
- $\text{median}(x) =$   $\text{median}(y) =$
- $m_x =$   $m_y =$

- **Dispersion:** We also typically want to know how spread out the data are relative to the center of the observed distribution. Again, there are several ways to measure dispersion.

1. **Sample variance:** The sample variance is the sum of the squared deviations from the sample mean, divided by the number of observations minus 1.

$$\text{Var}(X) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

Again, this is an *estimate* of the variance of a random variable; we divide by  $n-1$  instead of  $n$  in order to get an unbiased estimate.

2. **Standard deviation:** The sample standard deviation is the square root of the sample variance.

$$\text{SD}(X) = \sqrt{\text{Var}(X)} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

3. **Median absolute deviation (MAD):** The MAD is a different measure of dispersion, based on deviations from the median rather than deviations from the mean.

$$\text{MAD}(X) = \text{median}(|x_i - \text{median}(x)|)$$

Example: Using table above, calculate:

1.  $\text{Var}(X) =$   $\text{Var}(Y) = 8$
2.  $\text{SD}(X) =$   $\text{SD}(Y) =$
3.  $\text{MAD}(X) =$   $\text{MAD}(Y) =$

- **Covariance and Correlation:** Both of these quantities measure the degree to which two variables vary together, and are estimates of the covariance and correlation of two random variables as defined above.

1. **Sample covariance:**  $\text{Cov}(X, Y) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})$
2. **Sample correlation:**  $r = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X)\text{Var}(Y)}}$

Example: Using above table, calculate:

1.  $\text{Cov}(X, Y) =$

2.  $r =$

## 2 R and L<sup>A</sup>T<sub>E</sub>X Installation Information

### 2.1 R Installation Instructions

1. Download R from <http://cran.r-project.org/mirrors.html>.<sup>13</sup>
2. Once you've picked a mirror download R for your operating system.
3. When it's done downloading, install R.
4. (Optional) Download and install the most recent version of RStudio Desktop from <http://www.rstudio.com/products/rstudio/download/>.<sup>14</sup>
  - Make sure you install R before RStudio. Not doing so could potentially cause issues.

### 3 L<sup>A</sup>T<sub>E</sub>X Installation Instructions

LaTeX is a powerful document preparation system. It allows you to output high-quality and customizable PDF documents. L<sup>A</sup>T<sub>E</sub>X is a document markup language, meaning that it consists of syntax that specifies to the program how the document is to be formatted - that is, typesetting instructions. More common examples of markup languages are HTML and XML. Markup embedded in a L<sup>A</sup>T<sub>E</sub>X document conveys formatting and processing specifications to the T<sub>E</sub>X engine. It then allows you to output fancy PDFs like this one (and just about everything else used in the Prefresher)

To begin using L<sup>A</sup>T<sub>E</sub>X you need to things:

- L<sup>A</sup>T<sub>E</sub>X front end or text editor to write a .tex file
- L<sup>A</sup>T<sub>E</sub>X compiler that processes the T<sub>E</sub>X code you've written and outputs the document you want

**Windows** users:

- Compiler: MiKTeX
- Some editors: Texmaker , TeXnic Center , LyX. <sup>15</sup>

**Mac** users:

- Compiler: MacTeX
- Some editors: TeXShop , Aquamacs , Texmaker , TextWrangler , Latexian

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<sup>13</sup>It doesn't really matter which mirror you use.

<sup>14</sup>RStudio is the best IDE (integrated development environment) for R. It allows you to simultaneously see your R Console, multiple scripts of code, all the objects in your workspace, your working directory, plots, installed packages, and help files. You don't need RStudio (or any IDE) to run R, but it makes your life a lot easier.

<sup>15</sup>Windows users: only download the installer (not the bundle) since you've already downloaded MiKTeX

## 4 Greek Letters and Math Symbols

### 4.1 Greek Letters

Name	Lowercase	Uppercase	Typical usage
alpha	$\alpha$	A	often the intercept in a regression
beta	$\beta$	B	often denotes the parameters in a model
gamma	$\gamma$	$\Gamma$	uppercase denotes a special counting function
delta	$\delta$	$\Delta$	denotes a difference
epsilon	$\epsilon, \varepsilon$	E	denotes a very small number or error
zeta	$\zeta$	Z	
eta	$\eta$	H	sometimes denotes variance/standard deviation
theta	$\theta, \vartheta$	$\Theta$	often used for radians
iota	$\iota$	I	
kappa	$\kappa$	K	can denote curvature
lambda	$\lambda$	$\Lambda$	eigenvalues; parameter of a Poisson regression
mu	$\mu$	M	mean
nu	$\nu$	N	
xi	$\xi$	$\Xi$	
omicron	$\omicron$	O	
pi	$\pi, \varpi$	$\Pi$	3.1415...; a probability function; product function
rho	$\rho, \varrho$	P	correlation
sigma	$\sigma, \varsigma$	$\Sigma$	variance/standard deviation; summation function
tau	$\tau$	T	sometimes denotes variance/standard deviation
upsilon	$\upsilon$	$\Upsilon$	
phi	$\phi, \varphi$	$\Phi$	denotes the PDF and CDF of a normal distribution
chi	$\chi$	X	denotes the chi-square distribution
psi	$\psi$	$\Psi$	
omega	$\omega$	$\Omega$	

### 4.2 Mathematical Symbols

#### 4.2.1 Equivalency symbols

Symbol	Meaning	L <sup>A</sup> T <sub>E</sub> X code
=	equals	=
≠	not equal to	<code>\neq</code>
>	greater than	>
<	less than	<
≥	greater than or equal to	<code>\geq</code>
≤	less than or equal to	<code>\leq</code>
∝	proportional to	<code>\propto</code>
≈	approximately equal to	<code>\approx</code>
∝	distributed as (or indifference)	<code>\sim</code>
≡	equivalent to; set equal to; defined as	<code>\equiv</code>
⋈	preferred to	<code>\succ</code>

### 4.2.2 Common mathematical symbols

Symbol	Meaning	L <sup>A</sup> T <sub>E</sub> X code
$\infty$	infinity	<code>\infty</code>
$\pm$	plus or minus	<code>\pm</code>
$\mp$	minus or plus	<code>\mp</code>
$\perp$	perpendicular	<code>\perp</code>
$\parallel$	parallel	<code>\parallel</code>
$ $	given	<code>\mid</code>
$\cdot$	dot; times	<code>\cdot</code>
$\cdots$	dots	<code>\cdots</code>
$\mathfrak{R}$	all real numbers	<code>\mathfrak{R}</code>
$\bar{x}$	x bar	<code>\bar{x}</code>
$\hat{x}$	x hat	<code>\hat{x}</code>

### 4.2.3 Function symbols

Symbol	Meaning	L <sup>A</sup> T <sub>E</sub> X code
$\sqrt{x}$	square root	<code>\sqrt{x}</code>
$\sqrt[n]{x}$	$n^{\text{th}}$ root	<code>\sqrt[n]{x}</code>
$!$	factorial	<code>!</code>
$\sum_{i=1}^n$	summation notation	<code>\sum\limits_{i=1}^n</code>
$\prod_{i=1}^n$	production notation	<code>\prod\limits_{i=1}^n</code>
$\lim_{n \rightarrow \infty}$	limits notation	<code>\lim\limits_{n \to \infty}</code>
$\int$	integral	<code>\int</code>

### 4.2.4 Logical symbols

Symbol	Meaning	L <sup>A</sup> T <sub>E</sub> X code
$\therefore$	therefore	<code>\therefore</code>
$\forall$	for all	<code>\forall</code>
$\exists$	there exists	<code>\exists</code>
$\implies$	logical “then” statement	<code>\implies</code>
$\iff$	if and only if	<code>\iff</code>
iff	if any only if	<code>iff</code>
$\in$	is an element of	<code>\in</code>
$\ni$	such that	<code>\ni</code>
s.t.	such that	<code>s.t.</code>
QED	end of proof (quod erat demonstrandum)	<code>QED</code>
W.R.T.	with respect to	<code>W.R.T.</code>

**4.2.5 Set notation symbols**

Symbol	Meaning	L <sup>A</sup> T <sub>E</sub> X code
$\{ \}$	set	<code>\{ \}</code>
$\emptyset$	empty set	<code>\emptyset</code>
$\cup$	union	<code>\cup</code>
$\cap$	intersection	<code>\cap</code>
$\subset$	subset	<code>\subset</code>

You can look up the L<sup>A</sup>T<sub>E</sub>X code for other math symbols at <http://detexify.kirelabs.org/classify.html>