

# CS146

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October 2025

## 1 Lecture 1 - Basic Notation

### 1.1 Sums

#### 1.1.1 Basic Sums

Sigma notation makes use of the symbol  $\sum$  Basic sigma notation makes use of of lower and upper bounds that a bound variable iterates through in order to represent the sum of multiple elements

**Example 1.**

$$\sum_{k=2}^{11} k! = 2! + 3! + 4! + 5! + \dots + 10! + 11!$$

The lower bound is the initial condition and it ticks up by one to the upper bound and sums the expression with the values substituted in for the bound variable

#### 1.1.2 Sums over sets

Instead of giving a range for the sum to sum over we can give it an arbitrary set of numbers to sum over

**Example 2.** Let  $A = \{1, 2, \pi\}$

$$\sum_{k \in A} 2^{k^2-1} = 2^{1^2-1} + 2^{2^2-1} + 2^{\pi^2-1}$$

If we let  $E = \{2, 4, 6, 8, \dots\}$  or be the set of even numbers we have two ways of expressing sums on this set

$$\sum_{k \in E} \frac{1}{2^k} = \sum_{k-even, k \geq 1} \frac{1}{2^k}$$

### 1.1.3 Infinite Sums

Some sums can have  $\infty$  as their upper bound such as

$$\sum_{k=1}^{\infty} \frac{1}{2^k}$$

AS we know that the common ratio is in the radius of convergence, the infinite series is the limit of the partial sums. We know

$$\sum_{k=1}^n x^k = \frac{1 - x^{n+1}}{1 - x}$$

The infinite sum there for is the limit of this expression when  $x$  is in the radius of convergence i.e  $|x| < 1$

$$\lim_{n \rightarrow \infty} \sum_{k=1}^n x^k = \lim_{n \rightarrow \infty} \frac{1 - x^{n+1}}{1 - x} = \frac{1}{1 - x}$$

### 1.1.4 Empty Sums

If we take a sum over the empty set it will always equal 0 (additive identity)

$$\sum_{k \in \emptyset} f(k) = 0$$

## 1.2 Products

Product notation works largely the same as summation notation and can be used for the expression of known functions such as the factorial

$$n! = \prod_{k=1}^n k = 1 \times 2 \times \cdots \times n$$

We can also take products over a set. Let  $X = \{1, 2, 3\}$

$$\prod_{k \in X} f(k) = f(1) \times f(2) \times f(3)$$

We also have the fact a product over the empty set is 1 (multiplicative identity)

$$\prod_{k \in \emptyset} f(k) = 1$$

This also gives us the definition of  $0! = 1$  as a sum from  $1 \rightarrow 0$  is the same as a product over the empty set as there are no elements in that range

### 1.3 Sets

The first set we have is the natural numbers

$$\mathbb{N} = \{0, 1, 2, \dots\}$$

Note this definition includes zero which can be contentious. If we have  $0 \in \mathbb{N}$  then we can define the natural as such

- $0 \in \mathbb{N}$
- $k \in \mathbb{N} \Rightarrow k + 1 \in \mathbb{N}$

This definition has a flaw as sets with more elements than just the natural numbers can fulfil this definition but it serves as a constructive definition.

From the Natural Numbers (more so the integers which is just two copies of the naturals) we can define further sets

$$\mathbb{Q} = \left\{ \frac{a}{b} : a \in \mathbb{Z}, b \in \mathbb{Z}, b \neq 0 \right\}$$

And if we have the real numbers we can also define another set (defining the real numbers is the role of analysis)

$$\mathbb{C} = \{a + bi : a \in \mathbb{R}, b \in \mathbb{R}\}$$

## 2 Lecture 2 - Proofs

Proofs are mathematical arguments that apply formal logical deductive steps to prove a proposition from a set of axioms. There are three general proof techniques being Direct proofs, Proof by Contradiction and Proof by Induction.

### 2.1 DirectThe empty tuple is a value of () and it also has a type of (). Proof

This is the simplest form of proof simply with direct application of arguments

**Proposition 1.** *For  $n \geq 2$*

$$\sum_{k=2}^n = \frac{(n-1)(n-2)}{2}$$

*Proof.* Fix  $n \geq 2$  and let  $S(n) = \sum_{k=2}^n$

$$S(n) = 1 + 2 + \dots + (n-1) + n$$

$$S(n) = n + (n-1) + \dots + 2 + 1$$

$$2S(N) = (n+2) + (n+2) + \dots + (n+2) + (n+2)$$

$$2S(N) = (n-1)(n+2)$$

$$S(n) = \frac{(n-1)(n+2)}{2}$$

□

## 2.2 Proof By Contradiction

This techniques works by making the assumption of the negation of the proposition and from there deriving a contradiction

**Proposition 2.**  $\sqrt{2} \notin \mathbb{Q}$

*Proof.* Assume that  $\sqrt{2} \in \mathbb{Q}$  then there exists a coprime pair  $x, y \in \mathbb{Z}, y \neq 0$  such that  $\sqrt{2} = \frac{x}{y}$

We can now say  $x = 2y^2$

This suggest  $x^2$  is even and there for  $x$  is even therefore  $x^2$  is a multiple of 4 meaning  $y^2$  is even so  $y$  is even so both  $x, y$  share a factor of 2 and are as such not coprime yielding a contradiction so  $\sqrt{2} \notin \mathbb{Q}$   $\square$

## 3 Lecture 3 - Induction

### 3.1 Definitions

An inductive proofs is a methods for proving things on ordered sets. This is most commonly  $\mathbb{N}$  or  $\mathbb{Z}^+$

Let  $C(n)$  be a predicate where  $n \in \mathbb{N}$  then we know  $\forall_{n \in \mathbb{N}} C(n)$  if we have

1. Base Case :  $C(0)$
2. Inductive Case :  $C(k) \Rightarrow C(k + 1)$

### 3.2 Example

I have skipped the simple example and have instead skipped to the harder example.

**Proposition 3.** Given  $n \in \mathbb{Z}$  let  $C(n) : n^3 - n$  is divisible by three

Proposition 3 cant be done directly by induction as it is not well ordered (no least element for the base case). Instead we can split this into two problems. First we can prove is for  $n \in \mathbb{N}$  then attempt to extend this proof to  $\mathbb{Z}^-$ .

**Proposition 4.** Given  $n \in \mathbb{N}$  let  $C(n) : n^3 - n$  is divisible by three

*Proof.*

- Base Case :  $C(0) : 0$  is divisible by three
- Inductive Case : (IH)  $C(k) : k^3 - k$  is divisible by three , Aim :  $C(k + 1) : (k + 1)^3 - (k + 1)$  is divisible by three

$$\begin{aligned}(k + 1)^3 - k &= k^3 + 3k^2 + 3k + k - 1 \\ &= (k^3 - k) + 3(k^2 + k)\end{aligned}$$

By the (IH) the first term is a multiple of three and adding it to another multiple of three gives overall a multiple of three.  $\square$

Now we want to extend this to negative integers

*Proof.* We already know for  $n \geq 0$  :  $C(n)$  is true, if  $n \leq 0$  then  $n^3 - n = -((-n)^3 - (-n))$ . The  $(-n)$  terms are positive so the previous proof applies and the negative of a multiple of three is also a multiple of three.  $\square$

By combining both of these proofs we get a proof of Proposition 3

## 4 Lecture 4 - Recurrence

**Definition 1.** A recurrence relation is one where the sequence is defined in terms of previous terms. These will also generally have a base case.

**Example 3.** Consider the following sequence defined by series

$$a_n = \sum_{k=2}^n k = \frac{(n-1)(n+2)}{2}$$

We can rewrite this as a recurrence relation as follows

$$a_i = \begin{cases} 2, & i = 2 \\ a_{i-1}, & i > 2 \end{cases}$$

What we want is for a way to go from recurrence relations to closed forms. In order to do this lets consider the following recurrence

$$F_n = F_{n-1} + F_{n-2}$$

This will have boundary conditions  $F_1 = 1$  and  $F_2 = 1$ . This can also be derived from a consideration of breeding pairs of rabbits. There is in general two methods that we can use to solve it, Characteristic polynomials and by generating functions (and a secret third way using matrices). Here we shall cover the first.

### 4.1 Characteristic Polynomials

#### 4.1.1 Fitting the recurrence

WE start by assuming we have a solution of the form  $\lambda^n$

$$\lambda^n = \lambda^{n-1} + \lambda^{n-2}$$

Assuming  $\lambda \neq 0$  and rearranging we get

$$\lambda^2 - \lambda - 1 = 0$$

This yields two values for lambda of  $\varphi$  and  $\bar{\varphi}$  where  $\varphi$  is the golden ratio. One thing to note is that neither of these though satisfy the boundary conditions.

### 4.1.2 Boundary Conditions

**Proposition 5.** *A linear combination of solutions to a recurrence relation is itself a solution.*

*Proof.* Here a proof for a second order relation is given but it is trivial to see how it generalises. Given a  $\lambda_1$  and  $\lambda_2$  such that

$$\lambda_1^n = s\lambda_1^{n-1} + r\lambda_1^{n-2}$$

$$\lambda_2^n = s\lambda_2^{n-1} + r\lambda_2^{n-2}$$

The terms

$$\alpha\lambda_1^n + \beta\lambda_2^n$$

Can be rewritten as

$$s(\alpha\lambda_1^{n-1} + \beta\lambda_2^{n-1}) + r(\alpha\lambda_1^{n-2} + \beta\lambda_2^{n-2})$$

By means of subbing in the fact they satisfy the relations. As such that can be seen to also satisfy the relation.  $\square$

## 5 Lecture 5

### 5.1 Summary of the method

The method is summarised as follows

- Assume  $\lambda^n$  is a solution
- Solve for lambda
- Take a general linear combination of these solutions
- Solve against the boundary conditions

We can also express a generalised recurrence relation of order  $k$  as follows

$$S_n = \sum_{r=1}^k a_r S_{k-r} + f(n)$$

This will come with  $k$  boundary condition in order to be soluble

### 5.2 Gaussian Elimination

For higher order recurrence relations there will be  $n$  simultaneous equations to solve in order to fit to the boundary conditions. This can be slow so we would like an algorithmic method to be able to solve this. One such method is using

Gaussian elimination. Gaussian elimination is concerned with the reduction of equations to triangular form. This is shown below.

$$\begin{aligned} a_{1,n}x_n &= b_1 \\ a_{2,n-1}x_{n-1} + a_{2,n}x_n &= b_2 \\ &\dots \end{aligned}$$

The general idea is that the  $k$ th equation is expressed in terms of the last  $k$  variables. The way this is done is by using the last equation to eliminate the first variable from each equation. Then the second last equation to eliminate the 2nd variable from the rest and so on. Once the entire process is done each variable is trivially solved for.

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## 6 Lecture 6

### 6.1 Homogeneity

As previously stated a general linear recurrence relation can be given as

$$S_n = \sum_{r=1}^k a_r S_{k-r} + f(n)$$

If we have the fact that  $f(n) \equiv 0$  we may say the equation is homogenous otherwise its non homogenous

### 6.2 Complex roots

Sometimes when solving for  $\lambda$  we will find that it has complex values. When this happens we have 3 solutions of what to do

1. Just do it normally and solve for

$$\alpha\lambda_1^n + \beta\lambda_2^n$$

2. You can split alpha and beta into real and complex parts and solve for those separately

$$(\alpha + \alpha'i)\lambda_1^n + (\beta + \beta'i)\lambda_2^n$$

3. You can take advantage of the fact complex roots come in conjugate pairs and solve

$$\alpha(\lambda_1^n + \lambda_2^n) + \beta(\lambda_1^n - \lambda_2^n)$$

This has a closely related trigonometric form given as follows

$$r^n(\alpha \cos n\theta + \beta \sin n\theta)$$

Where  $r$  is the modulus of the root and  $\theta$  is the argument. This is gotten by application of de Moivre's theorem.

## 7 Lecture 10

**Example 4.**

$$Q_n = \begin{cases} 4 & n = 2 \\ Q_{n-1} + n^2 & n \geq 3 \end{cases}$$

This has  $s = 1$  and  $d = 2$  where these are the orderes of the relation and the degree of the nonhomogenous section (polynmials).

As such we have only one root  $\lambda_1$  and expect the solution to look as follows

$$Q_n = \alpha_1 \lambda_1 + \sum_{i=0}^2 \beta_i n^{i+\mu}$$

From simple calculation we know that  $\lambda_1 = 1$  and this gives us also the  $\mu = 1$  so

$$Q_n = \alpha + \beta_0 n + \beta_1 n^2 + \beta_2 n^3$$

Consider the tower of hanoi where  $h$  is the number of discs. If  $h = 1$  it will take one moves. If  $h \geq 2$  then you take  $2H_{h-1} + 1$  moves where  $H_h$  is the moves needed for  $h$  discs. This allows us to generate a reccurence relation as follows

$$H_h = \begin{cases} 1 & h = 1 \\ 2H_{h-1} + 1 & h \geq 2 \end{cases}$$

Giving motivation to why non-homogenous reccurence relations are wanted to be solved.

When solving these non homegenous relations you may find you have not enough base cases in order to be able to solve for all of the coefficients. In the case that this has happened you use the reccurence relation in order to generate more definite cases.

We may want to consider informally why there is a polynomial term added on. Consider the relation

$$B_n = \begin{cases} B_0 & n = 1 \\ B_{n-1} + p(n) & n \geq 2 \end{cases}$$

We may consider a relation  $B'_n$  which is the homogenous part of  $B_n$ . As the only difference between the two is continually adding  $n$  we may say

$$B_n = B'_n + \sum_{k=3}^n p(k)$$

As a sum of polynomials is itself a polynomial of we may observe that we would expect the solution to be the homogenous solution plus a non homogenous part.

**Example 5.**

$$B_n = \begin{cases} 1 & n = 1, 2 \\ 5B_{n-1} - 6B_{n-2} + n & n \geq 3 \end{cases}$$

Another considered transformation is  $B'_n = B_n + \alpha + \beta n$ . Which represents a transformation of the final solution removing the non homogenous parts of the solution. Suppose  $n \geq 3$

$$\begin{aligned} B'_n &= 5B_{n-1} - 6B_{n-2} + n + \alpha + \beta n \\ &= 5(B'_{n-1} - \alpha - \beta(n-1)) - 6(B'_{n-2} - \alpha - \beta(n-2)) + n + \alpha + \beta \\ &= 5B'_{n-1} - 6B'_{n-2} + 2\alpha - 7\beta + n(2 + \beta + n) \end{aligned}$$

Solving  $\alpha, \beta$  to make the sequence homogenous corresponds to the solutions you would have gotten for solving the relation by the method given before

## 8 Lecture 11

Continuing from the last lecture for a non-homogenous relation  $A_n$  with a polynomial non homogenous part of order  $n$  we may consider the complementary relations  $A'_n = A_n + g(n)$ . Here  $g(n)$  is some polynomial of deg at least  $n$  so that it makes the recurrence for  $A'_n$  homogenous. Once you have solved for the polynomial you then solve the homogenous part of the relation and use the transform to get the solution to the non homogenous equation. Consider the relation

$$Q_n = \begin{cases} 4 & n = 2 \\ Q_{n-1} + n^2 & n \geq 3 \end{cases}$$

You may consider the transform  $Q'_n = Q_n + \alpha + \beta n + \gamma n^2$  as for the linear case a linear transform worked so you may assume the same would carry forward.

$$\begin{aligned} B'_n &= Q_{n-1} + n^2 + \alpha + \beta n + \gamma n^2 \\ &= Q'_{n-1} - \alpha - \beta(n-1) - \gamma(n-1)^2 + n^2 + \alpha + \beta n + \gamma n^2 \\ &= Q'_{n-1} + \beta + \gamma(2n-1) + n^2 \end{aligned}$$

This is now impossible to make homogenous as we cannot eliminate the  $n^2$  term. By thinking back to the method for solving we can recall due to the root of 1 being present in the homogenous part the polynomial part of the solution was shifted up by a factor of  $n$  such that the solution was a cubic. This is why  $g$  is at least the degree of the polynomial part of the relation. For the above example above the appropriate transform would be  $Q'_n = Q_n + \alpha + \beta n + \gamma n^2 + \delta n^3$ . In order to formally prove such notion we need to look at some more maths.

### 8.1 Falling Power

**Definition 2.** Let the order  $m$  falling power be given by

$$x^m = x \cdot (x-1) \cdots (x-m+1) = \prod_{k=1}^m (x-k+1) = \frac{x!}{(x-m)!}$$

Note  $x^0 = 1$

**Theorem 1.** Suppose  $p(x)$  is a polynomial of degree  $n$ . There are unique numbers  $a_0, \dots, a_d$  such that

$$p(x) = \sum_{k=0}^d a_k x^k$$

*Proof.* We will take induction on  $n$  and appreciate that

$$p(x) = \sum_{k=0}^d \beta_k x^k$$

Base Case:  $d = 0$

$$p(x) = \beta_0 = \beta_0 x^0 = \beta_0 x^0$$

So true

Inductive Step : Suppose  $d > 0$  and for any polynomial of degree  $f \leq d - 1$  that the aim is true.

$$p(x) = \sum_{k=0}^d a_k x^k$$

. Let  $\alpha_d = \beta_d$  and let  $q(x) = p(x) - \alpha_d x^d$  which is a degree of order at most  $d - 1$  as the terms of order  $d$  cancel out as their coefficients are the same but negative. By the hypothesis  $q(x)$  can be shown as falling powers up do  $d - 1$ . And as  $q(x) + \alpha_d x^d = p(x)$

$$\begin{aligned} p(x) &= q(x) + \alpha_d x^d \\ &= \sum_{k=0}^{d-1} a_k x^k + \alpha_d x^d \\ &= \sum_{k=0}^d a_k x^k \end{aligned}$$

□

## 9 Lecture 12

### 9.1 difference operator $\Delta$

This operation is somewhat the discrete analogue of the derivative

**Definition 3.** LET  $f : \mathbb{N} \rightarrow \mathbb{R}$  we may define fhte difference  $(\Delta)$  as follows

$$(\Delta f)(n) = f(n+1) - f(n)$$

**Example 6.** Consider a function  $f : \mathbb{N} \rightarrow \mathbb{R}$  such that  $f(x) = x^3$ .

$$\begin{aligned} (\Delta f)(n) &= (n+1)^3 - n^3 \\ &= 3n^2 + 3n + 1 \end{aligned}$$

The difference operator also satisfies linearity allowing it to distribute over the sum of functions.

**Proposition 6.** For any function  $f : \mathbb{N} \rightarrow \mathbb{R}$

$$f(n) = f(1) + \sum_{k=1}^{n-1} (\Delta f)(k)$$

This can be considered the discrete analogue of the fundamental theorem of calculus. This version of the proposition assumes that  $0 \notin \mathbb{N}$ . If you do include zero swap 1 for 0

*Proof.*

$$\begin{aligned} f(1) + \sum_{k=1}^{n-1} (\Delta f)(k) &= f(1) + \sum_{k=1}^{n-1} f(k+1) - f(k) \\ &= f(1) + \sum_{k=1}^{n-1} f(k+1) - \sum_{k=1}^{n-1} f(k) \\ &= f(1) + \sum_{k=2}^n f(k) - \sum_{k=1}^{n-1} f(k) \\ &= f(1) + f(n) - f(1) \\ &= f(n) \end{aligned}$$

□

The trick used in order to cancel down the sum is known as telescopic.

**Proposition 7.** Product rule : Let there be a function  $f : \mathbb{N} \rightarrow \mathbb{R}$

$$(\Delta(f \cdot g))(x) = (\Delta f)(x)g(x+1) + f(x)(\Delta g)(x)$$

*Proof.*

$$\begin{aligned} &(\Delta f)(x)g(x+1) + f(x)(\Delta g)(x) \\ &= (f(x+1) - f(x))g(x+1) + f(x)(g(x+1) - g(x)) \\ &= f(x+1)g(x+1) - f(x)g(x+1) + f(x)g(x+1) - f(x)g(x) \\ &= f(x+1)g(x+1) - f(x)g(x) \\ &= (\Delta(f \cdot g))(x) \end{aligned}$$

□

## 9.2 Combining the two

**Proposition 8.** *Falling Power rule :  $(\Delta)x^m = mx^{m-1}$ . Where  $m \geq 1$*

*Proof.* We will do this proof by induction on  $m$ . With  $m \geq 1$

- Base case  $m = 1$

$$\Delta x^1 = (x + 1) - x = 1 = 1x^0$$

- Inductive Step. Assume it holds for some  $m \geq 1$ . We now aim to show it for  $m + 1$

$$\begin{aligned}\Delta x^{m+1} &= \Delta(x^1 \cdot (x - 1)^m) \\ &= (x + 1 - x)(x - 1 + 1)^m + x \cdot (\delta(x - 1)^m) \\ &= (x)^m + x \cdot m(x - 1)^{m-1} \\ &= (x)^m + m(x)^m \\ &= (m + 1)(x)^m\end{aligned}$$

□

## 10 Lecture 15

Suppose we have a set  $A$  such that  $|A| = n \in \mathbb{N}$  how many subsets are there of size  $k$ . This is given by the binomial coefficients as  $\binom{n}{k}$

**Proposition 9.** *Suppose  $A$  is a set such that  $|A| = n \in \mathbb{N}$  the number of ways this can be ordered is  $n!$ .*

*Proof.* There are  $n$  positions we are able to place in the elements.

- For the first position we have  $n$  options
- For the second position we have  $n - 1$  options
- ...
- For the  $(i + 1)$ th position we have  $n - i$  options
- ...
- For the  $n$ th position we have 1 choice

By the product rule for combinatorics (also known as the fundamental principle of counting) we may take the product of all of these will give us the total number of orderings which is

$$n \times (n - 1) \times \dots \times 2 \times 1 = n!$$

□

We can further generalise this proposition

**Proposition 10.** Suppose  $A$  is a set such that  $|A| = n \in \mathbb{N}$  the number of ordering of length  $k$   $\frac{n!}{(n-k)!}$ .

*Proof.* There are  $k$  position we are able to place in the elements.

- For the first position we have  $n$  options
- For the second position we have  $n - 1$  options
- ...
- For the  $(i + 1)$ th position we have  $n - i$  options
- ...
- For the  $k$ th position we have  $(n - (k - 1))$  choices

By the product rule for combinatorics (also known as the fundamental principle of counting) we may take the product of all of these will give us the total number of orderings which is

$$n \times (n - 1) \times \dots \times (n - k + 1) = \frac{n!}{(n - k)!}$$

□

Now we return to the first claim and aim to prove this

**Proposition 11.** The number of  $k$ -element subsets of a set  $a$  such that  $|A| = n \in \mathbb{N}$

$$\binom{n}{k} = \frac{n!}{(n - k)!}$$

*Proof.* Suppose  $|A| = n \in \mathbb{N}$ . We can call  $N_k$  the number of  $k$  element subsets of  $A$ .

We can make the observation for each  $k$  elements subset  $B \subseteq A$  the number of orderings of  $B$  is  $k!$ . From here we can define a set  $\Gamma$  such that for all  $B \in \Gamma$  contains all of the orderings of  $B$ . Therefore we can say  $|\Gamma| = k!N_k$ .  $\Gamma$  is also the set of orderings of elements of  $k$  elements so we can also say  $\Gamma = \frac{n!}{(n - k)!}$ . And as such we can conclude

$$\begin{aligned} k!N_k &= \frac{n!}{(n - k)!} \\ N_k &= \frac{n!}{k!(n - k)!} = \binom{n}{k} \end{aligned}$$

□

**Proposition 12.** for all  $x, y \in \mathbb{R}$  and  $n \geq 0$

$$(x + y)^n = \sum_0^n \binom{n}{k} x^k y^{n-k}$$

*Proof.* We may expand the bonomial as

$$\underbrace{(x+y)(x+y)\cdots(x+y)}_{n \text{ times}}$$

Each monomial is made up by choosing one of  $x, y$  from each parenthesis. For a specific monomial  $x^n y^{n-k}$  The coefficient is the number of ways we can choose  $x$  from the  $n$  parentheses. This value is  $\binom{n}{k}$  which becomes the coefficient of each monomial.  $\square$