

Sequences and Summations

Section 2.4

Section Summary

- Sequences
 - Ex: Geometric Progression, Arithmetic Progression
- Recurrence Relations
 - Ex: Fibonacci Sequence
- Summations

Introduction

- **Sequences** are ordered lists of elements.
 - 1, 2, 3, 5, 8
 - 1, 3, 9, 27, 81,
- Sequences arise throughout mathematics, computer science, and in many other disciplines, ranging from botany to music.
- We will introduce the terminology to represent sequences and sums of the terms in the sequences.

Sequences

Definition: A *sequence* is a function from a subset of the integers (usually either the set $\{0, 1, 2, 3, 4, \dots\}$ or $\{1, 2, 3, 4, \dots\}$) to a set S .

- The notation a_n is used to denote the image of the integer n . We can think of a_n as the equivalent of $f(n)$ where f is a function from $\{0, 1, 2, \dots\}$ to S .
- We call a_n a *term* of the sequence.

Sequences

Example: Consider the sequence $\{a_n\}$ where $a_n = \frac{1}{n}$

$$\{a_n\} = a_1, a_2, a_3, a_4, \dots$$

$$1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots$$

Geometric Progression

Definition: A *geometric progression* is a sequence of the form: $a, ar, ar^2, \dots, ar^n, \dots$ where the *initial term* a and the *common ratio* r are real numbers.

Ex:

1. Let $a = 1$ and $r = -1$. Then:

$$\{b_n\} = b_0, b_1, b_2, b_3, b_4, \dots = 1, -1, 1, -1, 1, \dots$$

2. Let $a = 2$ and $r = 5$. Then:

$$\{c_n\} = c_0, c_1, c_2, c_3, c_4, \dots = 2, 10, 50, 250, 1250, \dots$$

3. Let $a = 6$ and $r = 1/3$. Then:

$$\{d_n\} = d_0, d_1, d_2, d_3, d_4, \dots = 6, 2, \frac{2}{3}, \frac{2}{9}, \frac{2}{27}, \dots$$

Arithmetic Progression

Definition: An *arithmetic progression* is a sequence of the form: $a, a + d, a + 2d, \dots, a + nd, \dots$ where the *initial term* a and the *common difference* d are real numbers.

Ex:

1. Let $a = -1$ and $d = 4$:

$$\{s_n\} = s_0, s_1, s_2, s_3, s_4, \dots = -1, 3, 7, 11, 15, \dots$$

2. Let $a = 7$ and $d = -3$:

$$\{t_n\} = t_0, t_1, t_2, t_3, t_4, \dots = 7, 4, 1, -2, -5, \dots$$

3. Let $a = 1$ and $d = 2$:

$$\{u_n\} = u_0, u_1, u_2, u_3, u_4, \dots = 1, 3, 5, 7, 9, \dots$$

Strings

Definition: A *string* is a finite sequence of characters from a finite set (an alphabet).

- Sequences of characters or bits are important in computer science.
- The *empty string* is represented by λ .
- The string *abcde* has *length* 5.

Recurrence Relations

Definition: A *recurrence relation* for the sequence $\{a_n\}$ is an equation that expresses a_n in terms of one or more of the previous terms of the sequence, namely, a_0, a_1, \dots, a_{n-1} , for all integers n with $n \geq n_0$, where n_0 is a nonnegative integer.

- The *initial conditions* for a sequence specify the terms that precede the first term where the recurrence relation takes effect.

A sequence is called a *solution* of a recurrence relation if its terms satisfy the recurrence relation.

Questions about Recurrence Relations

Example 1: Let $\{a_n\}$ be a sequence that satisfies the recurrence relation $a_n = a_{n-1} + 3$ for $n = 1, 2, 3, 4, \dots$ and suppose that $a_0 = 2$. What are a_1 , a_2 and a_3 ?
[Here $a_0 = 2$ is the initial condition.]

Solution: We see from the recurrence relation that

$$a_1 = a_0 + 3 = 2 + 3 = 5$$

$$a_2 = 5 + 3 = 8$$

$$a_3 = 8 + 3 = 11$$

Questions about Recurrence Relations

Example 2: Let $\{a_n\}$ be a sequence that satisfies the recurrence relation $a_n = a_{n-1} - a_{n-2}$ for $n = 2, 3, 4, \dots$ and suppose that $a_0 = 3$ and $a_1 = 5$. What are a_2 and a_3 ?
[Here the initial conditions are $a_0 = 3$ and $a_1 = 5$.]

Solution: We see from the recurrence relation that

$$a_2 = a_1 - a_0 = 5 - 3 = 2$$

$$a_3 = a_2 - a_1 = 2 - 5 = -3$$

Fibonacci Sequence

Definition: Define the *Fibonacci sequence*, f_0, f_1, f_2, \dots , by:

- Initial Conditions: $f_0 = 0, f_1 = 1$
- Recurrence Relation: $f_n = f_{n-1} + f_{n-2}$

Example: Find f_2, f_3, f_4, f_5 and f_6 .

Answer:

$$f_2 = f_1 + f_0 = 1 + 0 = 1,$$

$$f_3 = f_2 + f_1 = 1 + 1 = 2,$$

$$f_4 = f_3 + f_2 = 2 + 1 = 3,$$

$$f_5 = f_4 + f_3 = 3 + 2 = 5,$$

$$f_6 = f_5 + f_4 = 5 + 3 = 8.$$

Solving Recurrence Relations

- Finding a formula for the n th term of the sequence generated by a recurrence relation is called *solving the recurrence relation*.
- Such a formula is called a *closed formula*.
- Many methods for solving recurrence relations (Ch. 8)
- Here we illustrate by example the method of *iteration* in which we need to guess the formula. The guess can be proved correct by the method of induction (Ch. 5).

Iterative Solution Example

Method 1: Working upward, **forward substitution**

Let $\{a_n\}$ be a sequence that satisfies the recurrence relation $a_n = a_{n-1} + 3$ for $n = 2, 3, 4, \dots$ and suppose that $a_1 = 2$.

$$a_2 = 2 + 3$$

$$a_3 = (2 + 3) + 3 = 2 + 3 \cdot 2$$

$$a_4 = (2 + 2 \cdot 3) + 3 = 2 + 3 \cdot 3$$

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$$a_n = a_{n-1} + 3 = (2 + 3 \cdot (n - 2)) + 3 = 2 + 3(n - 1)$$

Iterative Solution Example

Method 2: Working downward, **backward substitution**

Let $\{a_n\}$ be a sequence that satisfies the recurrence relation $a_n = a_{n-1} + 3$ for $n = 2, 3, 4, \dots$ and suppose that $a_1 = 2$.

$$\begin{aligned}a_n &= a_{n-1} + 3 \\&= (a_{n-2} + 3) + 3 = a_{n-2} + 3 \cdot 2 \\&= (a_{n-3} + 3) + 3 \cdot 2 = a_{n-3} + 3 \cdot 3 \\&\quad \cdot \\&\quad \cdot \\&\quad \cdot \\&= a_2 + 3(n-2) = (a_1 + 3) + 3(n-2) = 2 + 3(n-1)\end{aligned}$$

Financial Application

Example: Suppose that a person deposits \$10,000.00 in a savings account at a bank yielding 11% per year with interest compounded annually. How much will be in the account after 30 years?

Let P_n denote the amount in the account after n years. P_n satisfies the following recurrence relation:

$$P_n = P_{n-1} + 0.11P_{n-1} = (1.11) P_{n-1}$$

with the initial condition $P_0 = 10,000$

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Financial Application

$$P_n = P_{n-1} + 0.11P_{n-1} = (1.11) P_{n-1}$$

with the initial condition $P_0 = 10,000$

Solution: Forward Substitution

$$P_1 = (1.11)P_0$$

$$P_2 = (1.11)P_1 = (1.11)^2 P_0$$

$$P_3 = (1.11)P_2 = (1.11)^3 P_0$$

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$$P_n = (1.11)P_{n-1} = (1.11)^n P_0 = (1.11)^n 10,000$$

$$P_n = (1.11)^n 10,000 \quad (\text{Can prove by induction, covered in Ch. 5})$$

$$P_{30} = (1.11)^{30} 10,000 = \$228,992.97$$

Useful Sequences

TABLE 1 Some Useful Sequences.

<i>n</i> th Term	First 10 Terms
n^2	1, 4, 9, 16, 25, 36, 49, 64, 81, 100, ...
n^3	1, 8, 27, 64, 125, 216, 343, 512, 729, 1000, ...
n^4	1, 16, 81, 256, 625, 1296, 2401, 4096, 6561, 10000, ...
2^n	2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, ...
3^n	3, 9, 27, 81, 243, 729, 2187, 6561, 19683, 59049, ...
$n!$	1, 2, 6, 24, 120, 720, 5040, 40320, 362880, 3628800, ...
f_n	1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, ...

Example: Conjecture a formula for a_n if the first 10 terms of the sequence $\{a_n\}$ are 1, 7, 25, 79, 241, 727, 2185, 6559, 19681, 59047

Solution: $a_n = 3^n - 2$

Summations

- Sum of terms a_m, a_{m+1}, \dots, a_n from the sequence $\{a_n\}$
- The notation:

$$\sum_{j=m}^n a_j \qquad \sum_{j=m}^n a_j \qquad \sum_{m \leq j \leq n} a_j$$

represents

$$a_m + a_{m+1} + \dots + a_n$$

- The variable j is called the *index of summation*. It runs through all the integers starting with its *lower limit* m and ending with its *upper limit* n .

Summations

- More generally for a set S :

$$\sum_{s \in S} f(s)$$

- **Examples:**

- *If $S = \{2, 5, 7, 10\}$, then $\sum_{j \in S} j = 2 + 5 + 7 + 10$*

- $1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \dots = \sum_{i=1}^{\infty} \frac{1}{i}$

- $r^0 + r^1 + r^2 + r^3 + \dots + r^n = \sum_{j=0}^n r^j$

Geometric Series

Sums of terms of geometric progressions

$$\sum_{j=0}^n ar^j = \begin{cases} \frac{ar^{n+1} - a}{r - 1} & r \neq 1 \\ (n + 1)a & r = 1 \end{cases}$$

Proof: Let $S_n = \sum_{j=0}^n ar^j$

To compute S_n , first multiply both sides of the equality by r and then manipulate the resulting sum as follows:

$$\begin{aligned} rS_n &= r \sum_{j=0}^n ar^j \\ &= \sum_{j=0}^n ar^{j+1} \end{aligned}$$

By the distributive property

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Geometric Series

$$= \sum_{j=0}^n ar^{j+1}$$

From previous slide.

$$= \sum_{k=1}^{n+1} ar^k$$

Shifting the index of summation with $k = j + 1$.

$$= \left(\sum_{k=0}^n ar^k \right) + (ar^{n+1} - a)$$

Removing $k = n + 1$ term and adding $k = 0$ term.

$$= S_n + (ar^{n+1} - a)$$

Substituting S for summation formula

$$\therefore rS_n = S_n + (ar^{n+1} - a)$$

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Geometric Series

$$\therefore rS_n = S_n + (ar^{n+1} - a)$$

From previous slide.

$$rS_n - S_n = (ar^{n+1} - a)$$

Solving for S_n

$$S_n(r - 1) = (ar^{n+1} - a)$$

if $r \neq 1$

$$S_n = \frac{ar^{n+1} - a}{r - 1}$$

if $r = 1$

$$S_n = \sum_{j=0}^n ar^j = \sum_{j=0}^n a = (n + 1)a$$

QED

Some Useful Summation Formulae

TABLE 2 Some Useful Summation Formulae.

<i>Sum</i>	<i>Closed Form</i>
$\sum_{k=0}^n ar^k \ (r \neq 0)$	$\frac{ar^{n+1} - a}{r - 1}, r \neq 1$
$\sum_{k=1}^n k$	$\frac{n(n+1)}{2}$
$\sum_{k=1}^n k^2$	$\frac{n(n+1)(2n+1)}{6}$
$\sum_{k=1}^n k^3$	$\frac{n^2(n+1)^2}{4}$
$\sum_{k=0}^{\infty} x^k, x < 1$	$\frac{1}{1-x}$
$\sum_{k=1}^{\infty} kx^{k-1}, x < 1$	$\frac{1}{(1-x)^2}$

Geometric Series: We just proved this.

Later we will prove some of these by induction.

Proof in text (requires calculus)