

Math 21C

Kouba

Alternating Series Test (For Convergence Only)

DEFINITION : A series of the form

$$\sum_{n=1}^{\infty} (-1)^{n+1} a_n = a_1 - a_2 + a_3 - a_4 + a_5 - \dots,$$

where  $a_n > 0$  for all values of  $n = 1, 2, 3, 4, \dots$ , is called an *alternating series*. How can we test this series for convergence? We will need the following fact, which is given without proof.

FACT A : Assume that the sequence  $\{b_n\}$  satisfies the following two conditions :

1.)  $b_1 < b_2 < b_3 < b_4 < \dots$ , i.e.,  $b_n < b_{n+1}$  for  $n = 1, 2, 3, 4, \dots$  (The sequence is strictly increasing.) and

2.)  $b_n < C$ , a fixed constant, for  $n = 1, 2, 3, 4, \dots$  (The sequence is bounded.).

Then  $\lim_{n \rightarrow \infty} b_n = L$  for some finite number  $L$ .

Alternating Series Test : Consider the series  $\sum_{n=1}^{\infty} (-1)^{n+1} a_n$ . If the sequence  $\{a_n\}$  is posi-

tive (+), decreasing ( $\downarrow$ ), and  $\lim_{n \rightarrow \infty} a_n = 0$ , then the series  $\sum_{n=1}^{\infty} (-1)^{n+1} a_n$  converges.

Proof : Use the sequence of partial sums (even and odd separately). Since  $\{a_n\}$  is positive and decreasing, the following must be true :

$$s_2 = a_1 + (-a_2) < a_1,$$

$$s_4 = a_1 + \underbrace{(-a_2)}_{(-)} + a_3 + \underbrace{(-a_4)}_{(-)} < a_1,$$

$$s_6 = a_1 + \underbrace{(-a_2)}_{(-)} + a_3 + \underbrace{(-a_4)}_{(-)} + a_5 + \underbrace{(-a_6)}_{(-)} < a_1, \dots$$

and

$$s_{2n} = a_1 + \underbrace{(-a_2)}_{(-)} + a_3 + \underbrace{(-a_4)}_{(-)} + a_5 + \dots + \underbrace{(-a_{2n-2})}_{(-)} + a_{2n-1} + \underbrace{(-a_{2n})}_{(-)} < a_1, \dots;$$

also

$$s_2 = \underbrace{(a_1 - a_2)}_{(+)},$$

$$s_4 = (a_1 - a_2) + (a_3 - a_4) = s_2 + \underbrace{(a_3 - a_4)}_{(+)},$$

$$s_6 = (a_1 - a_2) + (a_3 - a_4) + (a_5 - a_6) = s_4 + \underbrace{(a_5 - a_6)}_{(+)}, \dots$$

and

$$s_{2n} = (a_1 - a_2) + (a_3 - a_4) + \cdots + (a_{2n-1} - a_{2n}) = s_{2n-2} + \underbrace{(a_{2n-1} - a_{2n})}_{(+)} > s_{2n-2}, \dots$$

thus, the sequence of even partial sums  $\{s_{2n}\} = \{s_2, s_4, s_6, s_8, \dots\}$  is increasing and bounded above by  $a_1$ . It follows from FACT A that

$$\lim_{n \rightarrow \infty} s_{2n} = L, \text{ for some finite number } L.$$

Now consider the sequence of odd partial sums  $\{s_{2n-1}\} = \{s_1, s_3, s_5, s_7, \dots\}$ . Note that

$$\begin{aligned} s_{2n} &= a_1 - a_2 + a_3 - a_4 + \cdots + a_{2n-1} - a_{2n} \\ &= (a_1 - a_2 + a_3 - a_4 + \cdots + a_{2n-1}) - a_{2n} \\ &= s_{2n-1} - a_{2n}, \end{aligned}$$

i.e.,

$$s_{2n-1} = s_{2n} + a_{2n}.$$

Taking the limit of both sides we get

$$\lim_{n \rightarrow \infty} s_{2n-1} = \lim_{n \rightarrow \infty} s_{2n} + \lim_{n \rightarrow \infty} a_{2n} = L + 0 = L.$$

Now the sequence of *all* partial sums  $\{s_n\} = \{s_1, s_2, s_3, s_4, s_5, \dots\}$  satisfies  $\lim_{n \rightarrow \infty} s_n = L$ .

Thus,

$$\sum_{n=1}^{\infty} (-1)^{n+1} a_n = \lim_{n \rightarrow \infty} s_n = L$$

and the alternating series converges by the sequence of partial sums test.

## Analysis of the Error (Remainder), $R_n$ , for a Convergent Alternating Series

Begin by separating the  $n$ th partial sum,  $s_n$ , and the error (remainder),  $R_n$ , for a convergent alternating series :

$$\sum_{n=1}^{\infty} (-1)^{n+1} a_n = \underbrace{a_1 - a_2 + a_3 - \cdots + (-1)^n a_n}_{\text{partial sum, } s_n} + \underbrace{(-1)^{n+1} a_{n+1} + (-1)^{n+2} a_{n+2} + \cdots}_{\text{error (remainder), } R_n}$$

It follows that the error satisfies

$$R_n = \begin{cases} a_{n+1} - a_{n+2} + a_{n+3} - a_{n+4} + \cdots, & \text{if } n \text{ is even} \\ -a_{n+1} + a_{n+2} - a_{n+3} + a_{n+4} - \cdots, & \text{if } n \text{ is odd.} \end{cases}$$

Using the same (+)/(-) analysis as in the proof of the Alternating Series Test, we can conclude that ...

- 1.) If  $n$  is even, then  $0 < R_n < a_{n+1}$ .
- 2.) If  $n$  is odd, then  $-a_{n+1} < R_n < 0$ .

In general, it is then true that

$$-a_{n+1} < R_n < a_{n+1},$$

i.e.,

$$|R_n| < a_{n+1}$$

for  $n = 1, 2, 3, 4, \dots$ .