Epi-Cesaro Convergence

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Abstract. Since the turn of the century there have been several notions of convergence for subsets of metric spaces appear in the literature. Appearing in as a subset of these notions is the concepts of epi-convergence. In this paper we present definitions of epi-Cesaro convergence for sequences of lower semicontinuous functions from $X$ to $[-\infty, \infty]$ and Kuratowski Cesaro convergence of sequences of sets. Also we characterize the connection between epi-Cesaro convergence of sequences of functions and Kuratowski Cesaro convergence of their epigraphs.

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1. INTRODUCTION AND BACKGROUND

During the past five decades new concepts of convergence for sequences of functions have been appearing in mathematical analysis. These concepts are especially designed to approach the limit of sequences of variational problems and are called variational convergence. With each type of variational problem
is associated a particular concept of convergence. In [3], Attouch developed
a convergence theory for sequences of functions, called epi-convergence. This
concepts of convergence has natural applications in all branches of optimization
theory. In this paper, we will introduce a new convergence kind for sequences
of function sequences and call it epi-Cesaro convergence.

To facilitate this process we recall the basic definitions and concepts (see
[1]-[16]). The Cesaro limit superior and Cesaro limit inferior a real sequence
\((x_n)\) are defined as follow:

\[ (C,1) - \limsup_n x_n = \inf \left\{ \frac{1}{m} \sum_{k=1}^{m} x_k : m \geq n \right\} \]

and

\[ (C,1) - \liminf_n x_n = \sup \left\{ \frac{1}{m} \sum_{k=1}^{m} x_k : m \geq n \right\} . \]

The sequence \(x = (x_n)\) is Cesaro convergent if and only if

\[ (C,1) - \limsup_n x_n = (C,1) - \liminf_n x_n. \]

The following characterization may be found in [9].
A sequence \((x_n)\) is Cesaro convergent to \(\ell\), provided

\[ \lim_{m \to \infty} \frac{1}{m} \sum_{k=1}^{m} x_k = \ell. \]

In this case we shall write \((C,1) - \lim x_n = \ell.\)

The notion of Cesaro convergence extend the usual concept of convergence
in a non-trivial fashion. We know that a convergent sequence is a Cesaro
convergent sequence. But the converse does not holds in general. For example,
the sequence \(x = (x_n) = (1, 0, 1, 0, ...)\) is Cesaro convergent \(\frac{1}{2}\), however this
sequence is not convergent.

Let \((X,d)\) be a metric space. An extended real-valued function \(f : X \to
[\infty, \infty]\) on a metric space \(X\) is called lower semicontinuous provided its epi-
graph

\[ epi f \equiv \{(x, \alpha) : x \in X, \alpha \in \mathbb{R} \text{ and } \alpha \geq f(x)\} \]
is closed subset of \(X \times \mathbb{R}\). Given a sequence \((f_n)\) of lower semicontinous
functions from \(X\) into \([\infty, \infty]\), we say that \((f_n)\) is epi-convergent to \(f\), and
we write \(f = \lim_{n} f_n\), provided at each \(x \in X\), the following two conditions
both hold:

(i) whenever \((x_n)\) is convergent to \(x\), we have \(f(x) \leq \liminf f_n (x_n)\);
(ii) there exists a sequence \((x_n)\) convergent to \(x\) such that \(f(x) = \lim f_n (x_n)\).
Although closely connected to the notion of pointwise convergence it is neither stronger nor weaker. In fact, certain of functions have different pointwise and epi-limits. Consider the sequence

\[ f_n(x) = \begin{cases} 0, & \text{if } x = \frac{1}{n} \\ 1, & \text{if } x \neq \frac{1}{n} \end{cases} \]

that pointwise convergent to the function \( h(x) = 1 \) for all \( x \) and epi-convergent to

\[ f(x) = \begin{cases} 0, & \text{if } x = 0 \\ 1, & \text{if } x \neq 0 \end{cases} \]

The epi-limit takes into account the behaviour of the \( f \) in the neighborhood of 0, whereas the pointwise limit restricts attention to what happens with the \( f_n \) at the point 0.

2. Main Results

**Definition 2.1.** Let \((X,d)\) be a metric space, for every \( x \in X \), let us denote the system of the neighbourhood of \( x \) by \( U(x) \). With any sequence \((f_n)\) of lower semicontinuous functions from \( X \) into \([-\infty, \infty]\) are associated two Cesaro limit functions:

(iii) The epi-Cesaro limit inferior of the sequence \((f_n)\), denoted by \((C,1) - \text{li}_e f_n\) is defined by

\[ (C,1) - \text{li}_e f_n(x) = \sup_{V \in U(x)} (C,1) - \liminf_n \inf_{u \in V} f_n(u). \]

(iv) The epi-almost limit superior of the sequence \((f_n)\), denoted by \((C,1) - \text{ls}_e f_n\) is defined

\[ (C,1) - \text{ls}_e f_n(x) = \sup_{V \in U(x)} (C,1) - \limsup_n \inf_{u \in V} f_n(u). \]

**Definition 2.2.** Let \((X,d)\) be a metric space and \((f_n)\) be a sequence of lower semicontinuous functions from \( X \) into \([-\infty, \infty]\). This sequence \((f_n)\) is said to be epi-Cesaro convergent at \( x \), if the following equality holds:

\[ (C,1) - \text{li}_e f_n(x) = (C,1) - \text{ls}_e f_n(x). \]

This common value is then denoted \((C,1) - \text{lim}_e f_n(x)\):

\[ (C,1) - \text{lim}_e f_n(x) = (C,1) - \text{li}_e f_n(x) = (C,1) - \text{ls}_e f_n(x). \]

For lower semicontinuous functions, equivalent definition can be given as following.

**Definition 2.3.** Given a sequence \((f_n)\) of lower semicontinuous function on a metric space \((X,d)\), we say that \((f_n)\) is epi-Cesaro convergent to \( f \) provided at each \( x \in X \), the following two conditions both hold:
(v) whenever \((x_n)\) is Cesaro convergent to \(x\), we have
\[ f(x) \leq (C, 1) - \liminf f_n(x_n); \]

(vi) there exists a sequence \((x_n)\) Cesaro convergent to \(x\) such that
\[ f(x) = (C, 1) - \lim f_n(x_n). \]

In this case we write \((C, 1) - \lim e f_n = f\).

The notion of pointwise Cesaro convergence is neither stronger nor weaker
than epi-Cesaro convergence. In fact, there exist some functions that have
different pointwise Cesaro and epi-Cesaro limits.

**Example 2.4.** Let
\[
    a_k = \begin{cases} 
        (-1)^n, & \text{if } k = n^2 \quad k = 1, 2, 3, \ldots \\
        0, & \text{otherwise.}
    \end{cases}
\]

Define the following function sequence:
\[
    f_n(x) = \sum_{k=1}^{n} a_k.
\]

Since
\[
    \frac{1}{k^2} \sum_{i=1}^{k^2} \sum_{l=1}^{i} a_l = \frac{k^2 - (k - 1)^2 + (k - 2)^2 - (k - 3)^2 + \ldots + 2^2 - 1}{k^2} \\
    = \frac{(1^2 + 3^2 + 5^2 + \ldots + k^2) - (2^2 + 4^2 + 6^2 + \ldots + (k - 1)^2)}{k^2} = \frac{1}{2} \frac{k + 1}{k}
\]
if \(k\) is odd and
\[
    \frac{1}{k^2} \sum_{i=1}^{k^2} \sum_{l=1}^{i} a_l = \frac{(k - 1)^2 - (k - 2)^2 + (k - 3)^2 - (k - 4)^2 + \ldots + 2^2 - 1}{k^2} \\
    = \frac{(1^2 + 3^2 + 5^2 + \ldots + (k - 1)^2) - (2^2 + 4^2 + 6^2 + \ldots + (k - 2)^2)}{k^2} = \frac{1}{2} \frac{k - 1}{k}
\]
if \(k\) is even, the sequence \((f_n(x))\) is Cesaro convergent to the function \(f(x) = \frac{1}{2}\).

However this sequence is epi-Cesaro convergent to the function \(f(x) = -1\).

**Example 2.5.** If
\[
    f_n(x) = \begin{cases} 
        x^2, & \text{if } n \text{ is odd} \\
        0, & \text{if } n \text{ is even},
    \end{cases}
\]

then the sequence \((f_n(x))\) is Cesaro convergent to the function \(f(x) = \frac{x^2}{2}\) but
epi-Cesaro convergent to the function \(f(x) = 0\) that is \((C, 1) - \lim e f_n(x) = 0\).

**Example 2.6.** Let
\[
    a_k = \begin{cases} 
        (-1)^n, & \text{if } k = 2^n \quad k = 1, 2, 3, \ldots \\
        0, & \text{otherwise.}
    \end{cases}
\]
Define the following function sequence:

\[ f_n(x) = \sum_{k=1}^{n} a_k. \]

Since

\[
\frac{1}{2^k} \sum_{i=1}^{2^k} a_i = \frac{2^k - 2^{k-1} + 2^{k-2} - \ldots + 2 - 1}{2^k}
\]

\[
= 1 - \frac{1}{2} + \frac{1}{2^2} - \frac{1}{2^3} + \ldots + \frac{1}{2^{k-1}} - \frac{1}{2^k} = \frac{1}{3}(2 - \frac{1}{2^k})
\]

if k is odd and

\[
\frac{1}{2^k} \sum_{i=1}^{2^k} a_i = \frac{2^{k-1} - 2^{k-2} + 2^{k-3} - \ldots + 2 - 1}{2^k}
\]

\[
= \frac{1}{2} - \frac{1}{2^2} + \frac{1}{2^3} - \frac{1}{2^4} + \ldots + \frac{1}{2^{k-1}} - \frac{1}{2^k} = \frac{1}{3}(1 - \frac{1}{2^k})
\]

if k is even, we have \((C, 1) - \liminf f_n(x) = \frac{1}{3}\) and \((C, 1) - \limsup f_n(x) = \frac{2}{3}\),
that is the sequence \((f_n(x))\) is not Cesaro convergent. However this sequence
is epi-Cesaro convergent to the function \(f(x) = -1\).

**Definition 2.7.** Let \((A_n)\) be a sequence of closed subsets of metric space
\((X, d)\). We say that \((A_n)\) is Kuratowski Cesaro convergent to a closed subset
\(A\) of \(X\) provided \(A = (C, 1) - \text{Li} A_n = (C, 1) - \text{Ls} A_n\) where

\[ (C, 1) - \text{Li} A_n = \{ x \in X : \text{there exist a sequence } (a_n) \text{ Cesaro} \]
convergent to \(x\) with \(a_n \in A_n\) for all but finitely integers \(n\}\)

\[ (C, 1) - \text{Ls} A_n = \{ x \in X : \text{there exists positive integers} \]
n_1 < n_2 < n_3 < \ldots \text{and } a_k \in A_n \text{ such that } (C, 1) - \lim_{k \to \infty} a_k = x \}

in this case we write \(A = \text{(C, 1) - Lim A_n}\).

**Theorem 2.8.** Let \((X, d)\) be a metric space and \((f_n)\) be a sequence of lower
semicontinuous functions from \(X\) into \([{-\infty, \infty}]\). The Cesaro limit sets
\((C, 1) - \text{Li}(\text{epi} f_n)\) and \((C, 1) - \text{Ls}(\text{epi} f_n)\) are still epigraphs. They are equal respectively
to the epigraphs of \((C, 1) - \text{li} f_n\) and \((C, 1) - \text{li} f_n\) that is,

\[ (C, 1) - \text{Li}(\text{epi} f_n) = \text{epi}((C, 1) - \text{li} f_n) \quad (2.1) \]

and

\[ (C, 1) - \text{Ls}(\text{epi} f_n) = \text{epi}((C, 1) - \text{li} f_n) \quad (2.2) \]

**Proof.** Let us first prove \((2.1)\). By definition \((C, 1) - \text{Li}, (x, \alpha) \in (C, 1) - \text{Li}(\text{epi} f_n)\) if and only if for all \(V \in U(x)\) and for every \(\epsilon > 0\) there exist \(n \in \mathbb{N}\)
such that there exists \(x_k \in V\) satisfying

\[ \alpha + \epsilon > \frac{1}{m} \sum_{k=1}^{m} f_k(x_k). \]
for $m \geq n$.

This can be reformulated in the following way:

$$\alpha > \sup_{V \in U(x)} \inf_n \sup_{u \in V} \frac{1}{m} \sum_{k=1}^{m} f_k(u)$$

that is

$$\alpha > \sup_{V \in U(x)} \limsup_n \inf_{u \in V} \frac{1}{m} \sum_{k=1}^{m} f_k(u) = ((C, 1) - ls_{e}f_n)(x)$$

which means $(x, \alpha) \in epi((C, 1) - ls_{e}f_n)$.

In view of the definition of $(C, 1) - Li(epif_n)$, the proof of (2.2) follows from exactly the same argument as above. \hfill \Box

We are now able to state the main result of this paper and establish the equivalence between epi-Cesaro convergence of a sequence of functions and the Kuratowski Cesaro convergence of their epigraphs. It is direct consequence of Definition 2.3 and Theorem 2.8.

**Theorem 2.9.** Let $(X, d)$ be a metric space and $(f_n)$ a sequence of lower semi-continuous functions from $X$ into $[-\infty, \infty]$. The sequence $(f_n)$ is epi-Cesaro convergent if and only if the sequence of sets $(epif_n)$ is Cesaro convergent in the Kuratowski sense. In that case following equality holds:

$$epi((C, 1) - lim_{\epsilon}f_n) = (C, 1) - Lim(epif_n).$$

Theorem 2.9 allows us to view epigraphs, as epi-Cesaro convergence of a sequence of functions in terms of set Cesaro convergence.

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