ON THE SPACE* $(BV)$

BY

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1. Introduction. For the space $(AC)$ of functions $x(t)$ absolutely continuous on the interval $0 \leq t \leq 1$ it is natural, since $(AC)$ then becomes isomorphic with the space $(L)$ of Lebesgue integrable functions, to employ the metric

$$(x, y) = |x(0) - y(0)| + T_0^1(x - y),$$

where $T_0^1(x - y)$ stands for the total variation of $x(t) - y(t)$ on $0 \leq t \leq 1$. Until recently the few writers† who have considered the space $(BV)$ of functions of bounded variation have simply carried over to this larger space the metric of $(AC)$. Although with this metric $(BV)$ is a Banach space, it is not separable; perhaps it is partly on that account that $(BV)$ was so little studied.

In I Adams introduced for $(BV)$ the new metric

$$(x, y) = \int_0^1 |x(t) - y(t)| \, dt + |T_0^1(x) - T_0^1(y)|,$$

giving reasons for this choice. These reasons will not be repeated here, but by way of partial motivation one might make two observations: (i) an arbitrary function in $(AC)$ can be approximated (arbitrarily closely) in the metric $(1)$ by an inscribed polygonal function, but no function in the class $(BV) - (AC)$ can be so approximated;‡ (ii) the metric $(2)$ permits such approximation to an arbitrary function in $(BV)$. Hereinafter, unless otherwise specified, $(BV)$ shall always be understood to be metrized with $(2)$; although not then a Banach space, it is boundedly compact and contains a countable dense set of polygonal functions (see I).

Presumably the most important subsets of $(BV)$ are $(CBV)$, the set of continuous functions of bounded variation, and $(AC)$. With the metric $(1)$, $(AC)$ is a closed linear manifold in $(CBV)$ which in turn is a like manifold in $(BV)$, so it may be inferred at once that $(AC)$ is of first category in $(CBV)$ and of second category in itself, while $(CBV)$ is of first category in $(BV)$ and of second category in itself. When the metric $(2)$ is employed, however, the

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† For references see Adams, The space of functions of bounded variation and certain general spaces, these Transactions, vol. 40 (1936), pp. 421–438; later referred to as I.
‡ For an indication of this fact see Adams and Lewy, On convergence in length, Duke Mathematical Journal, vol. 1 (1935), pp. 19–26; especially p. 23. This paper will be referred to as AL.

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questions of category appear to be less trivial, and one of the main objects of this paper is to answer them.

As a preliminary we set forth in §2 a lemma on semi-continuity of the functional $T(x)$. In §1 of I we compared several kinds of convergence and indicated by example that certain kinds do not imply certain others,* in each case the example was one in which the limit function has an external saltus. That only such an example will serve this purpose will appear among the consequences of the lemma in §2, and of an analogous lemma in §5. In §3 we consider the questions of category just mentioned. With $(DBV)$ designating the set of discontinuous functions of bounded variation and $(CS)$ the set of continuous singular functions,† the critical issues in §3 are met by showing that $(DBV)$ is the sum of sets each closed and non-dense in $(BV)$ and that $(CBV) - (CS)$ is the sum of sets each closed and non-dense in $(CBV)$. In §4 we determine a base for $(BV)$. Finally, in §5, we examine similar questions which arise when $T(x)$ is replaced by $L(x)$, the Peano length of $x(t)$.

2. Semi-continuity of $T(x)$, with applications. A short time ago Adams and Clarkson‡ observed the rather obvious but none the less fundamental semi-continuity relation: $\lim_{n \to \infty} x_n(t) = x(t)$ everywhere on $(0, 1)$ implies $\lim \inf_{n \to \infty} T(x_n) = T(x)$. Although it was not expressly so stated, this result holds for $T(x) = \infty$ as well as for $T(x) < \infty$. Our first object here is to obtain a similar result when $x_n(t)$ is assumed to converge to $x(t)$ only on a dense set in $0 \leq t \leq 1$.

To avoid possible misunderstanding let us first set up the

**Definition.** An arbitrary function $x(t)$ will be said to have no external saltus if and only if at each point $t_i$, $0 \leq t_i \leq 1$, $x(t_i)$ satisfies the condition $\lim_{t \to t_i} x(t) \leq x(t_i) \leq \lim_{t \to t_i} x(t)$. The class of functions having no external saltus will be designated by $(N)$; its intersection with $(BV)$, by $(BVN)$. Clearly $x(t) \in (BVN)$ implies continuity of $x(t)$ at $t = 0$ and $t = 1$.

**Lemma 1.** The relation $x_n(t) \to x(t)$ on a dense set in $(0, 1)$, with $x(t) \in (BVN)$, implies $\lim \inf_{n \to \infty} T(x_n) \geq T(x)$.

The reader should have little difficulty in establishing this lemma.

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* See p. 423 of I.
† See, for example, Saks, *Théorie de l’Intégrale*, Warsaw, 1933, pp. 11 ff.
‡ Adams and Clarkson, *On convergence in variation*, Bulletin of the American Mathematical Society, vol. 40 (1934), pp. 413–417; to be referred to as AC.
§ The notation $(a, b)$ for an interval will always mean the closed interval $a \leq t \leq b$.
∥ In general we employ the symbol $T^*_v(x)$ for the total variation of $x(t)$ on $a \leq t \leq b$; in particular the limits $a, b$ will be omitted when it seems that no confusion can arise therefrom.
Although we do not intend to make use of it here, we may assert for the case $T(x) = \infty$

**Lemma 1'**. The relation $x_n(t) \to x(t)$ on a dense set in $(0, 1)$, when $T(x) = \infty$ but $x(t) \in \mathcal{N}$ and the set $E$ of its discontinuities of the second kind is either vacuous or possesses an isolated point,* implies $\lim_{n \to \infty} T(x_n) = \infty$.

**Proof.** For Case 1, $E$ vacuous, a proof can be constructed essentially in the same manner as for Lemma 1. In Case 2, $E$ not vacuous, let $t_i$ be an isolated point of $E$. If for example $x(t_i - 0)$ fails to exist, there must be an interval $(t_0, t_1)$ which contains no discontinuity of the second kind other than $t_i$; and $T'K(x) = \infty$. If $T(\alpha(x)) = \infty$ for any $\alpha$, $t_0 < \alpha < t_1$, the conclusion follows from Case 1; otherwise, for arbitrary $M$ there exists $t_2$ such that $T_0(x) > M$ and the conclusion is a consequence of Lemma 1.

That Lemma 1 fails to hold when $x(t)$ is permitted to have an external saltus at even a single point is clear from the simplest examples. That Lemma 1' ceases to be valid when $E$ has no isolated point is shown by $x_n(t) = 0$ for all $n$; $x(t)$ the characteristic function of the rationals.

The two following lemmas are immediate consequences.

**Lemma 2.** The relation $\int_0^1 |x_n(t) - x(t)| \, dt \to 0$, with $x(t) \in \mathcal{BV}$, implies $\lim inf_{n \to \infty} T(x_n) \geq T(x)$.

**Proof.** If the conclusion were false there would exist $\epsilon > 0$ and a subsequence $x_p(t)$ such that $T(x_p) < T(x) - \epsilon$ for all $p$. This subsequence, however, must contain a subsequence $x_q(t)$ convergent almost everywhere to $x(t)$; hence by Lemma 1 we have $\lim inf_{q \to \infty} T(x_q) \geq T(x)$, a contradiction.

**Lemma 2'.** The relation $\int_0^1 |x_n(t) - x(t)| \, dt \to 0$, when $T(x) = \infty$ but $x(t)$ is qualified as in Lemma 1', implies $\lim_{n \to \infty} T(x_n) = \infty$.

**Definition.** We shall employ $x_n(t) - dv \to x(t)$ as an abbreviation for the two conditions: $x_n(t) \to x(t)$ on a dense set in $(0, 1)$, and $T(x_n) \to T(x)$.

**Theorem 1.** The relation $x_n(t) - dv \to x(t)$ on $(0, 1)$, $[(x_n, x) \to 0]$, with $x(t) \in \mathcal{BV}$, implies that relation for every subinterval whose end-points are points of continuity of $x(t)$.

**Proof.** We need only show that $T_0(x_n) \to T_0(x)$ whenever $a$ is a point of continuity of $x(t)$. By Lemma 1 [Lemma 2] we have $\lim inf T_0(x_n) \geq T_0(x)$, $\lim inf T_0(x_n) \geq T_0(x)$; and $\lim sup T_0(x_n) > T_0(x)$ would imply

* From the proof it is evident that this lemma can be strengthened a little by considering right- and left-hand limits.

† We repeat that $(x, y)$ always refers to the metric (2) unless otherwise specified.
\[ \lim T^*_0(x_n) \geq \limsup T^a_0(x_n) + \liminf T^1_0(x_n) > T^a_0(x) + T^1_0(x) = T^*_0(x), \]
in contradiction to hypothesis.

That this theorem breaks down for subintervals having an end-point at a discontinuity of \( x(t) \) is apparent from simple examples.

In I we remarked that “if \((x_n, x)\)→0 and \(x(t)\) is discontinuous at even a single point, \(x_n(t)\) may fail to converge to \(x(t)\) at every point.” This can happen, however, only when \(x(t)\) has an external saltus, as we see from

**Theorem 2.** The relation \(x_n(t) - dv \rightarrow x(t)\) on \((0, 1)\) \([(x_n, x)\)→0\], with \(x_0(t)\)ε(BV), implies \(x_n(t)\)→\(x(t)\) at every point of continuity of \(x(t)\).

**Proof.** Let \(a\) be any such point of continuity. No loss of generality results from assuming \(a>0\); for if \(a=0\), we can deal with the interval \((0, 1)\) as we now deal with \((0, a)\). Denial of the conclusion implies the existence of \(\epsilon>0\) and a subsequence \(x_p(t)\) such that \(|x_p(a) - x(a)| > \epsilon\) for all \(p\). But there exists \(\delta>0\) such that

\[ |x(t) - x(a)| \leq T^a_0(x) = T^a_0(x) - T^1_0(x) < \epsilon/2 \text{ for } a - \delta < t < a; \]

and \(a - \delta < t < a\) contains a point \(t_1\) where \(x(t)\) is continuous. Hence, in view of Theorem 1, we have \(T^a_0(x_p) \rightarrow T^a_0(x) < \epsilon/2\). But the interval \(t_1 < t < a\) contains a point \(t_2\) for which \(x_p(t_2) \rightarrow x(t_2)\), and we have for \(p\) sufficiently large

\[ T^a_0(x_p) \geq T^a_0(x_p) \geq |x_p(t_2) - x_p(a)| > \epsilon/2. \]

From this contradiction the theorem is to be inferred.

**Corollary 1.** For \(x(t)\)ε(BV), the relations \(x_n(t) - dv \rightarrow x(t)\) and \((x_n, x)\)→0 are equivalent.

That the first condition implies the second is seen by aid of Theorem 2, the uniform boundedness of \(x_n(t)\), and Lebesgue’s convergence theorem. The reverse implication is an immediate consequence of Theorem 2.

**Definition.** For \(x(t)\)ε(BV) we define an associated function \(\hat{x}(t)\) thus:

\(\hat{x}(t) = x(t+0)\) for \(0 \leq t < 1\), \(\hat{x}(1) = x(1-0)\).  

**Definition.** For \(x(t)\)ε(BV) we define the sum of its external saltuses as \(S(x) = T(x) - T(\hat{x})\).

If at an interior point \(t_1\) of \((0, 1)\) the function \(x(t)\) has an external saltus, the magnitude of the “external part” of the saltus (or briefly, the external saltus) is commonly defined as

\[ \min |x(t_1) - x(t_1 - 0)|, |x(t_1) - x(t_1 + 0)|. \]

Using two results given by Hobson* one may show without difficulty that
\[ S(x) = 2\sum (\text{external saltuses at interior points}) \]
\[ + |x(0) - x(0 + 0)| + |x(1) - x(1 - 0)|. \]

**Theorem 3.** The relation \((x_n, x) \rightarrow 0\), with \(x(t) \in (BVN)\), implies \((x_n, x) \rightarrow 0\) and \(S(x_n) \rightarrow 0\).

**Proof.** Since \(x_n(t) = x_n(t)\) almost everywhere, we have \(\int_0^1 |\dot{x}_n(t) - x(t)| dt \rightarrow 0\); whence, by Lemma 2, \(\lim \inf T(\dot{x}_n) \geq T(x)\). But from \(T(x_n) = T(x_n) + S(x_n) \rightarrow T(x)\), \(S(x_n) \geq 0\), we infer \(T(x_n) \rightarrow T(x)\) and \(S(x_n) \rightarrow 0\).

That \((x_n, x) \rightarrow 0\) with \(x(t) \in (BV) - (BVN)\) in general fails to imply \(S(x_n) \rightarrow S(x)\) is evident from simple examples.

**Theorem 4.** The relation \((x_n, x) \rightarrow 0\), with \(S(x_n) \geq k > 0\) for all \(n\), implies \(S(x) \geq k\).

**Proof.** As in the proof of Theorem 3 we have \(\lim \inf T(\dot{x}_n) \geq T(\dot{x})\). But the relations
\[ T(x) = T(\dot{x}) + S(x) = \lim T(x_n) \geq \lim \inf T(\dot{x}_n) + \lim \inf S(x_n) \]
\[ \geq \lim \inf T(\dot{x}_n) + k \]
then imply \(k \leq S(x) + T(\dot{x}) - \lim \inf T(\dot{x}_n) \leq S(x)\).

3. **Questions of category.** Let us recall from I that when \((x, y) = 0\) we say that \(x\) is metrically equal to \(y\) and write \(x \equiv y\). An element of the metric space \((BV)\) is therefore a class of functions any two of which are metrically equal; for \(x \in (CBV)\) the class consists of only one function, but for \(x \in (DBV)\) it contains an infinite number of functions. Since category is essentially a metric property, it seems desirable now to consider \((BV)\) merely as a metric space rather than as a vector metric space, the elements of which are single functions (see I).

From the definition of \(\dot{x}(t)\) given above in \(\S 2\) it is easily seen that if two functions \(x(t), y(t)\) satisfy the condition \((x, y) = 0\), then \(\dot{x}(t) \equiv \dot{y}(t)\) on \((0, 1)\) and \(S(x) = S(y)\). Hence it is proper to set up the following

**Definition.** If \(x \in (BVN)\) and \(x(t)\) is an arbitrary function of the class constituting \(x\), \(\dot{x}(t)\) will be called the **representative of the element** \(x\). If \(x \in (DBV) - (BVN)\) and \(x(t)\) is an arbitrary function of the class constituting \(x\), any function \(x(t) = \ddot{x}(t)\) for \(0 \leq t \leq 1\), \(t \neq t_t\); \(x(t_t) = \ddot{x}(t_t) + k\), where \(t_t\) is any point of \((0, 1)\) and \(k\) is so chosen that \(|x(t_t) - x(t_t - 0)| + |x(t_t) - x(t_t + 0)|\) exceeds the saltus of \(\ddot{x}(t)\) at \(t_t\) by \(S(x)\), will be called a **representative of** \(x\).

**Lemma 3.** If \((x_n, x) \rightarrow 0\) and for each \(n\) some representative \(x_n(t)\) of \(x_n\) has a

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* Hobson, loc. cit., p. 335.
saltus \geq k > 0 \text{ at one or more points of } (0, 1), \text{ then some representative } x(t) \text{ of } x \text{ will have at one or more points a saltus } \geq k.

Proof. Let \( t_0 \) be a point where \( x_t(t) \) has a saltus \( \geq k \); let \( l \) be a limit point of the sequence \( t_n \); and let the subsequence \( t_n \to t \). In case \( S(x) > 0 \) let \( x(t) \) be the representative of \( x \) obtained by taking \( t_i \) in the foregoing definition as \( l \). Then, \( \delta \) being positive but arbitrarily small, set \( a_\delta = E(l - \delta \leq t \leq l + \delta) \cdot E(0 \leq t \leq 1) \) and designate by \( b_\delta \) the closure of the complement of \( a_\delta \) with respect to \( (0, 1) \). Since \( b_\delta \) consists either of one closed subinterval of \( (0, 1) \), or of two disjoint intervals of this nature, on each of which \( x(t) \) has no external saltus, we have \( \lim \inf_{n \to \infty} T_{b_\delta}(x_n) \geq T_{b_\delta}(x) \) by Lemma 1. Hence the relation

\[
\lim \sup T_{a_\delta}(x_n) + \lim \inf T_{b_\delta}(x_n) \leq \lim \left[ T_{a_\delta}(x_n) + T_{b_\delta}(x_n) \right] = \lim T_0(x_n) = T_0(x) = T_{a_\delta}(x) + T_{b_\delta}(x)
\]

implies

\[
\lim \sup T_{a_\delta}(x_n) \leq T_{a_\delta}(x) + T_{b_\delta}(x) - \lim \inf T_{b_\delta}(x_n) \leq T_{a_\delta}(x).
\]

But since \( t_n \to t \) we have \( \lim \sup T_{a_\delta}(x_n) \geq k \); whence \( T_{a_\delta}(x) \geq k \) for all \( \delta > 0 \) and \( \lim_{\delta \to 0} T_{a_\delta}(x) = k \). And this last limit is precisely the saltus of \( x(t) \) at \( l \).

Theorem 5. \( (DBV) \) is the sum of a countable number of sets each closed and non-dense in \( (BV) \).

Proof. Let \( E_m \) be the set of points \( x \in DBV \) each of which has a representative \( x(t) \) possessing at some point a saltus \( \geq 1/m \). Clearly \( DBV = \sum_{m=1}^{\infty} E_m \). By Lemma 3 each \( E_m \) is closed in \( (BV) \). That each \( E_m \) is non-dense in \( (BV) \) now follows from the fact (see I, §1) that \( (CBV) \) is dense in \( (BV) \).

Since \( (BV) \), being complete (see I, §1), is of second category in itself, \( (CBV) \) is of second category in \( (BV) \), and we have in the terminology of Denjoy

Corollary 2. \( (CBV) \) is a residual set in \( (BV) \).

Corollary 3. \( (CBV) \) is of second category in itself.

Corollary 4. \( (DBV) \) is of first category in itself.

Otherwise, for the decomposition \( DBV = \sum_{m=1}^{\infty} E_m \) employed in proving Theorem 5, the closure in \( DBV \) of at least one set \( E_m \) would contain a sphere \( K(x_0, r) \subset DBV \). Since \( DBV \) is dense in \( (BV) \), the closure in \( (BV) \) of this set \( E_m \) would then contain the corresponding sphere \( K_1(x_0, r) \subset (BV) \), thus yielding a contradiction.

We next consider the set \( (CS) \) of continuous singular functions; i.e., of
functions $x(t) \in (CBV)$ for which the derivative $x'(t)$ vanishes almost everywhere* on the interval $(0, 1)$.

**Theorem 6.** $(CBV) - (CS)$ is the sum of a countable number of sets each closed and non-dense in $(CBV)$.

**Proof.** For brevity we call the sum of a finite number of disjoint closed intervals $a_i \leq t \leq b_i$ ($i = 1, 2, \ldots, p$) an elementary figure, designate such a set generically by $R$ and its measure by $|R|$, and let $T_R(x)$ stand for $\sum_{i=1}^{p} T_{a_i}^{b_i}(x)$.

For each integer $m > 0$ we define the set $A_m$ of $(AC)$ as follows: $\alpha(t) \in A_m$ if and only if we have

$$T_0^1(\alpha) \geq \frac{1}{m}, \quad \text{and} \quad T_R(\alpha) \leq \frac{1}{2} T_0^1(\alpha)$$

for every elementary figure $R \subset (0, 1)$ with $|R| \leq 1/m$. Then the subset $E_m$ of $(CBV) - (CS)$ we define thus: $x(t) \in E_m$ if and only if

$$\alpha(t) \in A_m, \quad \text{where} \quad \alpha(t) = \int_0^t x'(s) \, ds.$$

Denoting by $\overline{E}_m (m = 1, 2, 3, \ldots)$ the closure of $E_m$ in $(CBV)$, we propose to show that

$$(CBV) - (CS) = \sum_{m=1}^{\infty} \overline{E}_m.$$

It is clear that each point of $(CBV) - (CS)$ belongs to $E_m$ for some $m$. From the fact (see I) that the polygonal functions are dense in $(CBV)$, it is easily apparent that $(CS)$ is likewise. Therefore if for some $m > 0$, $E_m$ were not in $(CBV) - (CS)$, there would exist a point $y \in (CS)$ and a sequence $x_n \in E_m$ such that $(x_n, y) \to 0$. Let $\alpha_n(t) = \int_0^t x_n'(s) \, ds$ and $\beta_n(t) = x(t) - \alpha_n(t)$. The relation $y \in (CS)$ implies the existence of an elementary figure $R$ such that

$$T_R(y) \geq T_0^1(y) - \frac{1}{4m}, \quad |R| \leq \frac{1}{m}.$$ 

In view of the corollary to Theorem 2 of AC and of the fact that $T(x_n) = T(\alpha_n) + T(\beta_n)$ on every elementary figure, we should then have

$$2T_0^1(y) - \frac{1}{2m} \leq 2T_R(y) = \lim 2T_R(x_n) = \lim [2T_R(\alpha_n) + 2T_R(\beta_n)]$$

$$\leq \lim \inf [T_0^1(\alpha_n) + 2T_0^1(\beta_n)].$$

* See, for example, Saks, loc. cit. If one chooses to exclude the functions $x(t) = \text{const.}$ from the set $(CS)$, the proof of Theorem 6 can easily be modified to show that $(CBV) - (CS)$ is still the sum of non-dense closed sets in $(CBV)$. 

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\[ \leq \limsup \left[ 2T_0^1(\alpha_n) + 2T_0^1(\beta_n) \right] - \liminf T_0^1(\alpha_n) \]
\[ = \limsup 2T_0^1(x_n) - \liminf T_0^1(\alpha_n) \leq 2T_0^1(y) - \frac{1}{m}, \]

a contradiction which implies the decomposition above stated. That \( \overline{E}_m \) \((m = 1, 2, 3, \cdots)\) is non-dense in \((CBV)\) follows from the fact that \((CS)\) is dense in \((CBV)\).

From Theorem 6 and Corollary 3 follows

**Corollary 5.** \((CS)\) is a residual set in \((CBV)\).

**Corollary 6.** \((CS)\) is of second category in itself.

An immediate consequence of Theorem 6 is

**Corollary 7.** \((AC)\) is of first category in \((CBV)\).

Since \((AC)\) is dense in \((CBV)\), reasoning of the sort used in proving Corollary 4 may be employed to prove

**Corollary 8.** \((AC)\) is of first category in itself.

A complete classification of functions of bounded variation according to external saltus, continuity, absolute continuity, and singularity leads to a decomposition of \((BV)\) into the following seven disjoint sets each of which is easily seen to be dense in \((BV):\)

\( (DBV) \cdot (S) \cdot (N), \)
\( (DBV) \cdot (BV-S) \cdot (N), \)
\( (DBV) \cdot (S) \cdot (BV-BVN), \)
\( (DBV) \cdot (BV-S) \cdot (BV-BVN), \)
\( (AC)\), \((CS)\), and
\( (CBV-AC-CS). \)

Combining these sets in all possible ways one obtains 126 distinct proper subsets of \((BV)\) concerning each of which several questions of category and Borel character can be raised. Many of these combinations appear decidedly artificial,* nevertheless it may be worthwhile to point out that all questions of category concerning them can now be answered. For in proving Corollary 4 we have essentially established the lemma: \( Q \subset \mathbb{R} \) and \( Q \) dense in \( \mathbb{R} \) imply that the category of \( Q \) in \( \mathbb{R} \) is the same as the category of \( Q \) in itself. By repeated application of this lemma we infer from the above results that \((CS)\) is a residual set in \((BV)\). Hence any one of the 126 subsets which contains [does not contain] \((CS)\) is of second [first] category in \((BV)\), in itself, and in any other of the subsets in question of which it is a part.

That \((AC)\) is not a \(G_\delta\) in \((CBV)\) may readily be inferred; but whether it is an \(F_\sigma\) remains among the numerous open questions concerning Borel character. We may remark, however, that not only \((CBV)\) but also \((CS)\) is a \(G_\delta\) in

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* Curiously enough, our first application of the results of this paper will involve one of these "artificial" combinations.
(BV) and is therefore homeomorphic to a complete metric space, according to a theorem of Alexandroff.*

4. **Bases.** A sequence of elements $x_i$ of a vector metric space $S$ is called a base for $S$ if and only if to an arbitrary element $x \in S$ there corresponds a unique sequence of constants $c_i$ such that $(\sum_{i=1}^{n} c_i x_i, x) \to 0$ with $1/n$. For the space $(C)$ of continuous functions Schauder† has constructed a base consisting of a sequence of polygonal functions. His argument makes clear that this sequence also constitutes a base for both $(AC)$ and $(CBV)$ with our metric; that it is not a base for either (BV) or (BVN), however, may readily be seen.

In contrast with the point of view in §3, we must now regard (BV) and (BVN) as vector metric spaces, whose elements are single functions. As a first step toward the determination of a base for (BV) we shall prove that Haar’s system of orthogonal functions‡ serves as a base for (BVN). We recall that each Haar function $x_i(t)$ is continuous at the end points of $(0, 1)$ and that otherwise $x_i(t) = [x_i(t-0) + x_i(t+0)]/2$, whence $x \in (BVN)$ and any linear combination $\sum_{i=1}^{n} c_i x_i \in (BVN)$.

Now let $x$ be an arbitrary element of (BVN). The function $x(t)$ is one of a set which constitutes an element of the space $(L)$ of Lebesgue integrable functions. Since the Haar system provides a base for $(L)$, there exists a unique sequence of constants $c_i$ satisfying the condition, $\int_{0}^{1} |\sum_{i=1}^{n} c_i x_i - x| dt \to 0$ with $1/n$; and these $c_i$ are the coefficients in the Fourier expansion of $x(t)$ in the Haar functions.§ But the partial sum $s_n(t)$ of this expansion is a step-function which, on each of its intervals of constancy, is the mean value of $x(t)$ on that interval.|| From the following lemma the fact that $T(s_n) \to T(x)$, whence $(\sum_{i=1}^{n} c_i x_i, x) \to 0$, is to be inferred.

**Lemma 4.** If $x(t) \in (BVN)$ and $\alpha_{pq}$ is any set of numbers satisfying the conditions $m_{pq} \leq \alpha_{pq} \leq M_{pq} \ (p = 1, 2, \ldots, 2^n; \ q = 0, 1, 2, \ldots )$, where

\[
\begin{align*}
m_{pq} &= \inf x(t) \\
M_{pq} &= \sup x(t)
\end{align*}
\]

for $(p - 1)/2^n \leq t \leq p/2^n$;

then $\sum_{p=1}^{2^n} |\alpha_{p+1, q} - \alpha_{pq}| \to T_0(x)$ as $q \to \infty$.

This is a consequence of a theorem of Hobson, loc. cit., p. 332.

* See, for example, Kuratowski, *Topologie I*, Warsaw, 1933, p. 200.
§ See Schauder, loc. cit., pp. 50–51.
|| See Haar, loc. cit., p. 367.
If to Haar’s system of orthogonal functions we add the function \( x_0(t) = 0 \) for \( 0 \leq t < 1 \), \( = 1 \) for \( t = 1 \), we obtain a base for \((BV)\). For an arbitrary function \( x(t) \in (BV) \) is metrically equal to \( \hat{x}(t) + s(t) \), where \( s(t) = 0 \) for \( 0 \leq t < 1 \), \( = S(x) \) for \( t = 1 \). From the above reasoning it is clear that constants \( c_i \) \( (i = 1, 2, 3, \ldots) \) can be uniquely determined so that \( \sum_{i=0}^{n} c_i x_i \to 0 \) with \( 1/n \), and from the relation \( T(\sum_{i=0}^{n} c_i x_i) = T(\sum_{i=0}^{n} c_i x_i) + T(c_0 x_0) = T(\sum_{i=0}^{n} c_i x_i) + c_0 \) it follows that with and only with \( c_0 = S(x) \) shall we have \( \sum_{i=0}^{n} c_i x_i \to 0 \). The uniqueness of the entire sequence \( c_i \) \( (i = 0, 1, 2, \ldots) \) may now be deduced without difficulty.

The question as to whether \((BV)\), or perhaps more likely \((BVN)\), has a base consisting wholly of continuous functions remains open.

5. Concerning the functional \( L(x) \). We now consider the question of analogues of the above results when \( T(x) \) is replaced by \( L(x) \), the Peano length of \( x(t) \), and the metric (2) by

\[
(3) \quad (x, y) = \int_0^1 |x(t) - y(t)| \, dt + |L_0(x) - L_0(y)|.
\]

The reader should have no considerable difficulty in establishing for \( L(x) \) the analogue of Lemma 1, which provides a basis for drawing conclusions parallel to those described in §§2, 3 prior to Theorem 6. Although the employment of the metric (3) leaves unaltered the category and Borel properties set forth in Theorem 5 and its corollaries, it does effect a change on the subsets of \((CBV)\). Employing as in the proof of Theorem 6 the notation

\[ x_n = \alpha_n + \beta_n, \quad x = \alpha + \beta; \quad \alpha_n, \beta_n \in (AC); \quad \beta_n, \beta \in (CS), \]

we have

**Lemma 5.** The relation \( (x_n, x) \to 0 \), with \( T(\beta_n) \geq k > 0 \) for all \( n \), implies \( T(\beta) \geq k \).

**Proof.** According to I, §1 we have in the notation of “convergence in length” \( x_n \to x, \alpha \to \alpha; \) from a theorem of Morse\(^*\) one may then infer \( (x_n - \alpha) \to (x - \alpha) \). By Theorem 1 of AL it follows that \( (x_n - \alpha) \to (x - \alpha) \), in the notation of “convergence in variation.” Hence we have \( T(x_n - \alpha) = T(\alpha_n - \alpha) + T(\beta_n) \to T(\beta) \), and from \( T(\alpha_n - \alpha) \geq 0 \) the conclusion follows.

**Theorem 7.** \((CBV) - (AC)\) is the sum of a countable number of sets each closed and non-dense in \((CBV)\).

**Proof.** Allowing \( E_m \) to denote the set of points \( x \in (CBV) - (AC) \) each of

\(^*\) Morse, *Convergence in variation and related topics*, these Transactions, vol. 41 (1937), pp. 48–83, Theorem 5.4.
which satisfies the condition \( T(\beta)^{-1} / m \), we clearly have \((CBV) - (AC) = \sum_{m=1}^\infty E_m\). By Lemma 5 each \( E_m \) is closed; since with the metric (3) the set \((AC)\) is dense* in \((CBV)\), each \( E_m \) is also non-dense.

**Corollary 9.** \((AC)\) is a residual set in \((CBV)\), and is of second category in itself.

**Corollary 10.** \((CS)\) is of first category in \((CBV)\), and is of second category in itself.

**Proof.** In fact \((CS)\) is a closed non-dense set† in \((CBV)\). For, by Theorem 1 of AL the relation \( x_n \rightarrow x \) implies \( x_n \rightarrow y \rightarrow x \); therefore, if \( x_n \in (CS) \) for all \( n \), we have for all \( t \)

\[
L_0(x_n) = L_0(0) + T_0(x_n) = t + T_0(x_n) \rightarrow L_0(x) = t + T_0(x),
\]

whence \( \{1 + [x'(t)]^2\}^{1/2} = 1 + |x'(t)| \) almost everywhere and \( x'(t) = 0 \) almost everywhere; so that if \( x \in (CBV) \), it also is in \((CS)\).

It is easily seen by example, however, that \((CS)\) has limit points in \((DBV)\). Let \( (CS) \) be the closure of \((CS)\) in \((BV)\). Since \((CS)\) is a closed set in a complete space (see I, §1), it is of second category in itself. We consider then \((CS) - (CS) \subset (DBV)\). Let \((DBV) = \sum_{m=1}^\infty E_m\) be the decomposition used in showing \((DBV)\) to be of first category in \((BV)\), i.e., the analogue for \( L(x) \) of Theorem 5, and let \( G_m = E_m \setminus \{CS - (CS)\} \). Since for each \( m \) the set \( E_m \) has no limit point in \((CBV)\), \( G_m \) has no limit point in \((CS)\). But \( (CS)\) is dense in \((CS)\); therefore \( \overline{G_m} \), the closure of \( G_m \) in \((CS)\), contains no sphere of \((CS)\). Thus \((CS) - (CS)\) is of first category in \((CS)\), and \((CS)\) is a residual set in \((CS)\). \((CS)\) is therefore of second category in itself.

By aid of Theorem 5.2 of Morse (loc. cit.) it can readily be proved that \((CS)\) is dense in \((S)\), so that \((CS) = (S)\); reasoning similar to that of the preceding paragraph then shows that \((S)\) is of second category in itself. That \((S)\) is of first category in \((BV)\) is easily seen. It may be remarked that \((AC)\) is a residual set in \((BV)\); that, of the 126 sets mentioned at the close of §3, any combination including \( (AC) \) [not including \((AC) \) and not contained in \((S)\)] is of second [first] category in \((BV)\), in itself, and in any other combination of which it is a part; and that most, if not all, of the questions concerning the category of \((S)\) and its subsets can be answered by the aid of results now in hand. We observe also that not only \((CBV)\) but also each of the sets \((AC)\), \((CS)\), and \((CBV) - (CS)\) is a \( G_\delta \) in \((BV)\) and therefore homeomorphic to a complete metric space.

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* See I, §1.

† By aid of Theorem 8 below one may show similarly that \((SN)\) is a closed non-dense set in \((BV)\).
With the metric (3), Schauder's base for $(C)$ is again a base for $(AC)$ and for $(CBV)$; and by aid of Theorem 5.2 of Morse (loc. cit.) it follows that the base obtained above in §4 for $(BV)$ with the metric (2) is also a base for $(S)$ with the metric (3). But Haar's system of orthogonal functions is not a base for $(BVN)$, and the question of bases for $(BVN)$ and for $(BV)$ we leave open.

One may use the notation $x_n(t) \rightarrow_{dl} x(t)$ on $(0, 1)$ to stand for the pair of conditions $x_n(t) \rightarrow x(t)$ on a dense set in $(0, 1)$ and $L(x_n) \rightarrow L(x)$. It is natural to inquire whether $x_n \rightarrow_{ dl} x$ implies $x_n \rightarrow_{ dv} x$. This question may be answered with the aid of the following lemma, whose proof will be left to the reader.

**Lemma 6.** For $x(t) \in (BV)$ it is possible to approximate $x(t)$ in length by an inscribed broken line whose "corners" are at points of continuity of $x(t)$.

**Theorem 8.** The relation $x_n(t) \rightarrow_{dl} x(t)$ on $(0, 1)$, with $x(t) \in (BVN)$, implies $x_n(t) \rightarrow_{ dv} x(t)$.

**Proof.** By Lemma 1 we have $\lim \inf T(x_n) \geq T(x)$. For given $\epsilon > 0$ there exists a broken line $B$ of the sort specified in Lemma 6 such that $L(B) > L(x) - \epsilon$. By aid of the analogue for $L(x)$ of Theorem 1 we may now pursue the argument used in establishing Theorem 1 of AL to complete the proof.

In Theorem 8 the qualification $x(t) \in (BVN)$ cannot be dispensed with, as the following example shows: $x(t) = 0$ for $0 \leq t < \frac{1}{2}$, $= 1$ for $t = \frac{1}{2}$, $= \frac{1}{2}$ for $\frac{1}{2} < t \leq 1$; $x_n(t) = \frac{1}{2}$ for $\frac{1}{2} < t \leq 1$ and all $n$; on $(0, \frac{1}{2})$, $x_n(t)$ a sequence of polygonal functions all having the same length $\frac{3}{2}$ and the same total variation $2^{1/2}$, converging uniformly to $x(t) = 0$ and with $x_n(0) = x_n(\frac{1}{2}) = 0$ for all $n$. We observe that an example of the same type shows that when $x(t)$ has an external saltus at even one point, the condition $x_n(t) \rightarrow x(t)$ on a dense set in $(0, 1)$, plus semi-continuity of $T(x)$ at $x$, does not imply semi-continuity of $L(x)$ at $x$.

We conclude with the following

**Corollary 11.** The condition $(x_n, x) \rightarrow 0$ in the metric (3), with $x \in (BVN)$, implies that condition in the metric (2).

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