Constructive law of large numbers with application to countable Markov chains

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AMS meeting, New Orleans, 2011
Convergence speed in the law of large numbers

- Typical laws of large numbers: higher moment assumptions. Convergence speed is an important part of the statement and the proof.

- In case of identically distributed, (pairwise) independent variables, the law of large numbers follows already from the existence of the expected value. In this case, the question of convergence speed is more subtle.

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Introduction

Effective convergence

- We will work in constructive metric spaces (which have a natural definition).
- A sequence of functions \( x_1(t), x_2(t), \ldots \) between constructive metric spaces converges effectively (pointwise) to \( y(t) \) if there is an upper semicomputable \( m(\epsilon, t) \) (with real values) such that for all \( t \), all \( \epsilon > 0 \) and every \( n \geq m(\epsilon, t) \) we have \( d(x_n(t), y(t)) \leq \epsilon \). We call \( m(\epsilon, t) \) the threshold function.
- We could have required \( m(\epsilon, t) \) to be computable as well as to take integer values (but not both).
- If \( m(\epsilon, t) \) does not depend on \( t \) then the convergence is effectively uniform in \( t \).
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If $m(\epsilon, t)$ does not depend on $t$ then the convergence is **effectively uniform** in $t$. 
It is sometimes more convenient to work with the inverse, inspired by the notion of “order function” in Schnorr:

A function $b(n, t)$ is a shrinkorder function if: it is upper semicomputable, with $b(n, t) \downarrow 0$ for all $t$.

**Proposition**

The sequence $x_1(t), x_2(t), \ldots$ converges effectively to $y(t)$ if and only if there is a shrinkorder function $b(n, t)$ with $d(x_n(t), y(t)) \leq b(n, t)$ for all $n, t$.

For the case of a sequence of numbers $x_n$, we can even require $b(n)$ to be computable.
Proposition

Let $z_n \geq 0$, $y = \sum_n z_n$. If $z_n, y$ are (uniformly) computable then the convergence is effective.
More generally, if the convergence is effective relative to $(z_n), y$.

Indeed, $b(n) = y - \sum_{i=1}^n z_n$ is a shrinkorder function.

**Detachment:** Faster computability of $z_n$ and $y$ does not imply faster convergence to $y$: these two convergences are detached from each other. Indeed, given an arbitrary computable shrinkorder function $b(n)$ with $b(0) = 1$, the sum of the series $z_n = b(n-1) - b(n)$ converges as slowly as $b(n)$.

We can make $b(n)$ computable even in linear time without making it decrease faster.

This remark applies to all main effectiveness results in the talk.
There are many, equivalent, ways to define computability of probability distributions. Our results are sufficiently interesting even if one confines interest to integer-valued random variables. In this case, the distribution $P$ is computable if and only if $P(x)$ is computable for all integers $x$.

**Proposition**

*There exists a computable distribution over the nonnegative integers, with a non-computable expected value.*

**Proof.** Let $\alpha_i = 0$ or $2^{-k}$ for some $k$, with noncomputable $\sum_i \alpha_i < 1$. Construct $p(n)$ gradually: If $\alpha_i = 0$ then add $2^{-i}$ to $p(0)$. If $\alpha_i = 2^{-k}$ then add $2^{-i}$ to $p(2^{i-k})$. \qed
Effective stochastic convergence

A sequence of random variables \(X_1, X_2, \ldots\) with joint probability distribution \(P\) effectively converges to \(Y\) in probability, or stochastically, if there is an upper semicomputable function \(m(\delta, \epsilon)\) such that \(n \geq m(\delta, \epsilon)\) implies \(P[|X_n - Y| > \delta] < \epsilon\).

We say that \(X_n \rightarrow Y\) almost surely, effectively, if the last inequality is replaced with \(P[\sup_{n \geq m(\delta, \epsilon)} |X_n - Y| > \delta] < \epsilon\).

**Proposition**

The sequence \(X_n\) converges to \(Y\) in probability effectively if and only if there are shrinkorder functions \(b_1(n), b_2(n)\) with the property

\[
P[|X_n - Y| > b_1(n)] \leq b_2(n)
\]

for all \(n\). Similar characterization holds for almost sure convergence.

Of course, we could make \(b_1(n) = b_2(n)\).
It is not surprising that an effective law of large numbers allows to compute the expected value:

**Proposition**

Let $X_1, X_2, \ldots$ be a sequence of identically distributed random variables with distribution $P$ and expected value $\mu$. If $\frac{1}{n} \sum_{i=1}^{n} X_i$ converges to $\mu$ effectively in probability, then $\mu$ is computable from $P$.

**Corollary**

If $\mu$ is not computable then even if the distribution $P$ is computable, the convergence to $\mu$ in the weak law of large numbers is not effective.

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The easy direction

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We have seen a computable distribution $P$ over the nonnegative integers, with a non-computable expected value.
Theorem (Constructive strong law)

Let $X_1, X_2, \ldots$ be a sequence of identically distributed, pairwise independent random variables with distribution $P$. Let $E|X| = \mu < \infty$. Let $S_n = \sum_{i=1}^{n} X_i$. The average $S_n/n$ converges to $EX$ effectively in $(P, \mu)$.

The earlier remark on detachment applies to this result, too: the speed of computability of $\mu$ does not influence directly the speed of convergence in the law of large numbers.
Straightforward constructivization of a textbook proof. The truncated variables

$$Y_n = X_n 1[|X_n| < n].$$

have variances, and even $\sum_{n>0} \text{Var} Y_n / n^2 < \infty$ (due to identical distribution), effectively. Prove the strong law for $Y_n$ first.

Bound the difference $X_n - Y_n$ using

$$P[ (\exists \ k \geq n) \ Y_k \neq X_k ] \leq \sum_{k \geq n} P[|X_k| \geq k] = \sum_{k \geq n} P[|X_1| \geq k].$$

The latter sum is a tail of $\sum_{k \geq 0} P[|X_1| \geq k]$, related to the tails of

$$\int_0^\infty P[|X_1| \geq t] \ dt = E|X_1|. $$
Let $T_0, T_1, T_2, \ldots$ be integer random variables in $[0, \infty]$, where $T_0$ has distribution $Q$ over $\mathbb{Z} \cap [0, \infty)$, and for $i > 0$ the values $T_i - T_{i-1} > 0$ are identically distributed with distribution $R$ and $E(T_i - T_{i-1}) = \mu < \infty$, and independent (also from $T_0$). Define

$$X_m = 1 \text{ if } (\exists i) \ m = T_i, \text{ and } 0 \text{ otherwise}.$$ 

$X_0, X_1, \ldots$ is called a (positive recurrent) delayed renewal sequence.

**Theorem**

$$\frac{1}{n} \sum_{i=1}^{n} X_i \text{ converges to } 1/\mu \text{ almost surely, effectively in } (Q, R, \mu).$$

The proof is rather routine from the law of large numbers.
Let $T^n(x, y) = P \left[ X_{k+n} = y \mid X_k = x \right]$ be the $n$-step transition matrix of a Markov chain $X_0, X_1, \ldots$ with a countable state space.

Let $P^x$ be the conditional distribution when starting from $x$ (this is determined by $T(x, y)$).

The chain is irreducible if all states are mutually accessible:

$$\pi_{x,y} = P^x \left[ (\exists \, n) \, X_n = y \mid X_0 = x \right] > 0.$$ 

The chain is aperiodic if the smallest period of the return time distribution, when starting from any state, is 1.

If the expected return time $m_x$ of state $x$ is finite then $x$ is called positive recurrent.
Let $T^n(x, y) = P [ X_{k+n} = y | X_k = x ]$ be the $n$-step transition matrix of a Markov chain $X_0, X_1, \ldots$ with a countable state space.

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The chain is **irreducible** if all states are mutually accessible:

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Markov chains

- Let \( T^n(x, y) = P \left[ X_{k+n} = y \mid X_k = x \right] \) be the \( n \)-step transition matrix of a Markov chain \( X_0, X_1, \ldots \) with a countable state space.
- Let \( P^x \) be the conditional distribution when starting from \( x \) (this is determined by \( T(x, y) \)).
- The chain is **irreducible** if all states are mutually **accessible**:
  \[
  \pi_{x, y} = P^x[ (\exists n) X_n = y \mid X_0 = x ] > 0.
  \]
- The chain is **aperiodic** if the smallest period of the return time distribution, when starting from any state, is 1.
- If the expected return time \( m_x \) of state \( x \) is finite then \( x \) is called **positive recurrent**.
Theorem

Assume that the chain with transition matrix $T$ is irreducible, aperiodic and positive recurrent. Then $(p_x = 1/m_x : x \in \mathcal{X})$ is a probability distribution, and

$$\lim_{k \to \infty} T^k(x, y) = p_y.$$ 

Computability of $T(x, y)$ does not imply the computability of the equilibrium distribution $p_x$, as the following example shows. Let $T(0, i) = 2^{-i}$. For $i > 0$ let $T(i, 0) = \alpha_i$, $T(i, i) = 1 - \alpha_i$ for some $0 < \alpha_i < 1$ to be determined. We have the expected return time

$$m_0 = \sum_{i>0} 2^{-i}/\alpha_i.$$ 

Choose computable $\alpha_i$ while still making $m_0$ uncomputable, similarly to the example of non-computable expected value.
The sequence $Y_n$ that is 1 if $X_n = y$ and 0 otherwise, is a delayed renewal sequence. By the law of large numbers for these, $\sum_{i=1}^{n} Y_n/n$ converges to $p_y = 1/m_y$ effectively almost surely relative to $(T(\cdot, \cdot), p_y)$. From this, it is routine to conclude:

**Theorem (Computable ergodic theorem)**

Let the stationary countable Markov chain $X_0, X_1, X_2, \ldots$ be irreducible, aperiodic and positive recurrent, with distribution $P$ (this includes both $T(x, y)$ and $p_x$). Then for an arbitrary bounded computable function $f$, 

$$
\frac{1}{n} \sum_{i=1}^{n} f(X_n) \rightarrow \mathbb{E} f(X_0)
$$

almost surely, effectively in $P$. 