Memory traces in dynamical systems

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Created 1/21/2011
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Abstract:

To perform nontrivial, real-time computations on a sensory input stream, biological systems must retain a short-term memory trace of their recent inputs. It has been proposed that generic high-dimensional dynamical systems could retain a memory trace for past inputs in their current state. This raises important questions about the fundamental limits of such memory traces and the properties required of dynamical systems to achieve these limits. We address these issues by applying Fisher information theory to dynamical systems driven by time-dependent signals corrupted by noise. We introduce the Fisher Memory Curve \( (FMC) \) as a measure of the signal-to-noise ratio \( (SNR) \) embedded in the dynamical state relative to the input \( SNR. \) The integrated \( FMC \) indicates the total memory capacity. We apply this theory to linear neuronal networks and show that the capacity of networks with normal connectivity matrices is exactly 1 and that of any network of N neurons is, at most, N. A nonnormal network achieving this bound is subject to stringent design constraints: It must have a hidden feedforward architecture that superlinearly amplifies its input for a time of order N, and the input connectivity must optimally match this architecture. The memory capacity of networks subject to saturating nonlinearities is further limited, and cannot exceed square root N. This limit can be realized by feedforward structures with divergent fan out that distributes the signal across neurons, thereby avoiding saturation. We illustrate the generality of the theory by showing that memory in fluid systems can be sustained by transient nonnormal amplification due to convective instability or the onset of turbulence.

Journal:
Proceedings of the National Academy of Sciences(USA)

Volume:
105

Pagination:
18970?18975

Date Published:
12/2008

Notes:

{PMID:} 19020074

Full Text:
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