# Closing the loop; Inverse-model learning with a nonlinear avian syrinx and sparse auditory coding.

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**Abstract (300 words)**

Control-theoretic inverse models are very useful for learning and generating flexible sensory-goal directed motor behaviors. We have recently proposed a simple eligibility-weighted Hebbian learning rule capable of provably forming inverse models in high dimensional linear networks by associating random motor explorations with their future sensory consequences. In this theory the inverse model forms in the synaptic connections from sensory to motor neurons, allowing the conversion of a sensory memory (for example a tutor song template) into the necessary motor pattern required to reproduce the sensory memory.

Here we study both a nonlinear extension of this model and analytically demonstrate the relationship between inverse models and mirror neurons. We test inverse model learning in a nonlinear mass-spring model of the avian syrinx and an efficient sparse sensory representation of sound. Our learning rule learns appropriate inverse models. The inverses we find are causal (map sensation to the same action) or predictive (map sensation to future action) depending on the stereotypy of the neural code for motor explorations. In a random code, the formed inverse is causal and maximally useful for feedforward motor control because it allows imitation of arbitrary sensory target sequences.

We also show mirror neurons naturally arise during inverse model learning. Mirroring of motor and sensory evoked activity is either in precise temporal register, reflecting predictive inverses associated with stereotyped motor codes, or temporary delayed, reflecting causal inverses associated with variable motor codes.

Overall, this work demonstrates that bird song can be learned in realistic models of sound production, sound perception, and synaptic learning rules, and creates new conceptual connections (consistent with differences between HVC/LMAN in birds) between the stereotypy of the motor code, the causal nature of a learned inverse model, and the temporal lag between sensory and motor responses of the mirror neurons it contains.

**References**

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