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QUADERNI DEL DIPARTIMENTO
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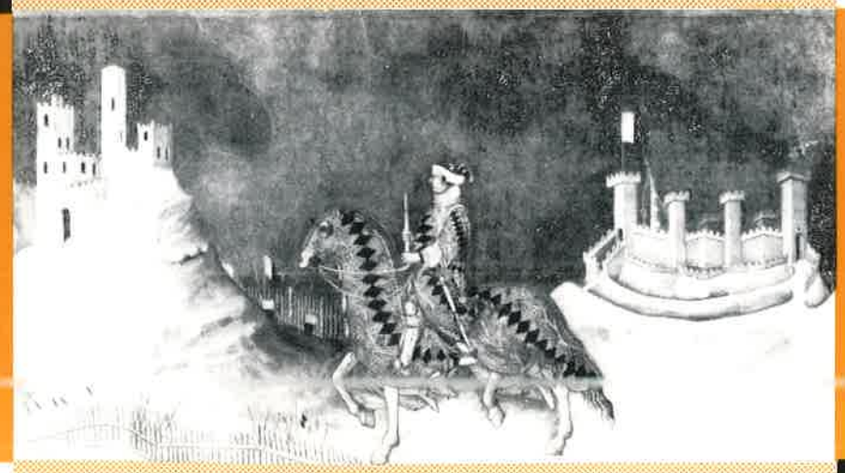
MAURO CAMINATI

PERCEPTION OF IGNORANCE IN A MACRO MODEL A NEURAL - NETWORK APPROACH



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Mauro Caminati

PERCEPTION OF IGNORANCE IN A MACRO MODEL A NEURAL-NETWORK APPROACH

Siena, Ottobre 1995

Abstract

This paper implements an integrated learning and decision procedure based on neural networks in the context of a 'large' overlapping generations economy. At every stage, the procedure is consistent with the assumption that the agent perceives her ignorance of the true model of the world. Asymptotic convergence properties are shown to be remarkably stronger than those prevailing under O.L.S. learning.

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1. Preliminaries*

A prominent effect of learning in macroeconomic models is the creation of a self-referential structure. When agents learn, they receive and process information on the evolution of the economy, as is affected by the activity of learning. It follows that this activity should be brought into one's view of the world and also that innovations in beliefs make the world non-stationary. Kurz (1994) shows that different beliefs can be statistically corroborated by the same evidence; in this sense, 'rational' beliefs may not be unique. These facts are sufficient to conclude that the economic environment which is relevant to macroeconomic analysis is characterized by genuine uncertainty, as opposed to risk. A fundamental premise of this note is that agents have typically *some* perception of their lack of information and the type of uncertainty they face in their choice situations, and behave accordingly. In the attempt to clarify the meaning of this 'fundamental premise' we refer to the notion of *awareness*. This has been recently characterized within systems of modal logic as the union of 'knowledge' and 'conscious ignorance'. For the scope of this paper the following intuitive definitions will suffice:

D.1 An agent is *uncertain* of x if she does not know x and she knows that she does not know x.

D.2 An agent is *aware* of x if she knows x, or she knows that she does not know x (cf. Modica and Rustichini (1994)).

In an environment with endogenous uncertainty boundedly-rational agents are information constrained and, in particular, do not know the true model of the world. One wonders whether a descriptively and cognitively plausible model of behaviour should also regard agents as being aware of the things they do not know. A short

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reflection reveals that the requirement would be too demanding. In complex environments boundedly-rational agents can be unaware of many things, for instance, of the prediction rule used by some other agent. It would be however equally unsatisfactory to assume (explicitly or implicitly) that agents are totally unaware of their ignorance. This paper starts from the premise that the most relevant choice situation in social sciences is one of *partial awareness*. In a complex world there are things which I am aware of and other things which I am unaware of. The crucial point is however captured by the assumption that if the agent is unaware of something, she is still aware that she *may be* unaware. A.1 below offers a more precise, but still non-formal statement of this assumption. Indeed, the possibility of providing axiomatic foundations to a formal model of the agent's view of her own model, and the relation of this issue with a decision-theoretic approach which can deal with situations of awareness of the possibility of unawareness are still open questions (cf. Modica and Rustichini (1993*b*), p. 27).

A.1 Let x be a proposition and $T(x)$ the truth value of x. Either the agent is aware of $T(x)$ and x, or else she is aware *there may exist* propositions of which she is unaware.

In environments in which A.1 is satisfied, the following holds true:

P.1 If there exists x such that the agent does not know $T(x)$, then she knows that she may not know the true model of the world.

For the purpose of this paper it is sufficient to remark that situations intuitively described by A.1 and P.1 are highly relevant to social science. Lack of information implies, through A.1, that the agent is at least aware that she may not be omniscient, hence that she may be wrong.

This is not the situation considered by a vast majority of macroeconomic models with boundedly-rational learning. Decisions are taken in these models *as if* learners were unaware that they may be wrong. From this perspective, the relevant examples in the literature can be divided into two broad classes.

In one class we find models in which the forecasting rule used by the agent is subjectively perceived as a true description of the world, while it is not, at least during learning. This class includes the work by Marcet and Sargent (1989a, 1989b) using Recursive Least Squares[1], the work by Evans and Honkapohja (1992a, 1992b) on the notion of Expectational stability, the deterministic models by Grandmont and Laroque (1986, 1989) and by Guesnerie and Woodford (1990), Woodford's "Learning to Believe in Sunspots", and many other examples. In all these models there is an implicit assumption on unawareness which conflicts with assumption A.1. The conflict is apparent already from the relation, as proposed by these models, between the agents' information set and the beliefs orienting their learning activity. Dissatisfaction with this relation can be mitigated by a strictly local interpretation. In a neighbourhood of a perfect-foresight or rational-expectations equilibrium which has been repeatedly visited in the past, learning and decision are locally approximated *as if* agents were holding a subjectively certain view of the world

The second class presents learners who do not have in their mind a unique model of the world, which is subjectively perceived as true. They may contemplate a given finite set of models and be uncertain on the truth value of them. Learning consists in this case in the process driving either the *selection* of a model (cf. Sacco (1994)), or the *averaging* on the set of models with adaptively changing weights (cf. Blume and Easley (1982)). Learners may otherwise not have one or more pre-defined models of the world, but form their forecasts through an adaptive process which gives rise to an endogenous 'internal representation' of the world. This is what occurs in the neural-network approach to learning (cf. Salmon: 1995). The models in this second class are equally at variance with assumption A.1, hence with proposition P.1. The conflict is now apparent in the relation between agents' information and their decision criteria. Although a subjectively-true view of the world is not in the agents' mind during learning, the decision criteria are exactly those which would be observed under certainty or in risk situations.

[1] It can de observed, in passing, that it is precisely the perception of the true model in a form like: $x_{t+1} = \beta x_t + \varepsilon_{t+1}$ (ε_{t+1} being i.i.d. and the "true" value of the parameter β being uncertain), what may subjectively justify the adoption of an Ordinary Least Squares estimation of β, in view of its optimality properties.

This paper claims that a failure to meet assumption A.1 reveals implausible features of learning and/or decision making. A plausible decision or learning theory is required to give agents: *(i)* a realistic amount of information and computing abilities, *(ii)* some perception of their lack of information in the sense of A.1, *(iii)* procedurally rational strategies. Section 2. presents a simple neural-network approach to decision making and learning, which is plausible in the sense defined above. Section 3. applies this approach to a simple overlapping-generations economy and reports some simulation results on the dynamics of this economy, with particular emphasis on its convergence and learning properties, as compared to those induced by other boundedly-rational learning procedures.

2. Plausible decision rules

The previous section touched upon a deep problem in decision theory. If agents face endogenous uncertainty and do not fully know the space of the possible states of the world, criteria for action do not have the same degree of determinateness which holds in standard decision theory. Recent attempts to propose plausible models of decision making under such conditions follow either the axiomatic approach, as for instance the "Case Based Decision Theory" of Gilboa and Schmeidler (1995), or a constructive approach, as is the case of the behavioural rules advocated by Arthur (1993) which try to 'mimic' observed human behaviour.

Despite the different epistemological orientation, these attempts suggest criteria for action which reveal at least two fundamental common principles:

A.2 The agent facing problem p takes an action a which depends upon the known pay-off consequences related to actions (effectively or hypothetically) taken in the past to solve *similar problems*. Experience is a fundamental guide to choice. In this sense, choice is 'backward looking'.

Remark 1 : Knowledge of the past gives information on the evolution of the economy, as is affected by the activity of learning. Thus, backward-looking behaviour is not insensitive to the fact that the other agents are performing the same task of learning.

Remark 2 : The experience, direct or inferred (on this more below), of the pay-off performance of the actions taken under given circumstances can be broad, if past history is long and the agent's memory large. This may occur for instance in case-based decision theory. Adaptive rules often assume a shorter memory, as is observed in the model considered in section 3.

A.3 Agents are aware that actions exclusively oriented by experience (direct or inferred) may fail to explore profitable opportunities. This introduces a search or innovation component in decisions.

Remark 3 : The importance of this component depends on aspiration levels which determine if and how far the agent is prepared to depart from experimented routines. An agent with low aspiration levels may be satisfied of landing in a possibly-local optimum and does not take the trouble of searching for the existence of a (different) global optimum.

It is worth observing that principles A.2 and A.3 (with the addition of a principle of "inertia", which can be regarded as less fundamental) provide a unifying framework also to the vast literature on adaptive learning in strategic games (cf. Marimon and McGrattan (1995)).

For the sake of simplicity, aspiration levels and the related innovation component in decisions are not considered in this paper. The analysis of section 3 can be however readily extended to cover also these factors. The following simplified operative definition of a plausible decision is hence introduced.

D.1 A decision taken under strong uncertainty is 'plausible' if and only if it is consistent with assumptions A.1 and A.2.

In environments with limited information an economic decision problem is associated to a forecasting problem. The macroeconomic literature on boundedly-rational learning has almost invariably considered the two problems explicitly and separately. The decision process is thus logically divided into two stages. In the first

stage the agent chooses a forecast; in the second stage she chooses the economic action which is optimal, if the forecast is correct. The separation just described has two shortcomings. In the first place the pay-off consequence of the forecast is typically identified with a statistical measure of the predictive power. The undesirable implication is that learning becomes an economic goal per se, or, equivalently, economic actions are in the end oriented by non economic (e.g. statistical) criteria[2]. In the second place, since economic choice is described as if it were conditioned on a subjectively certain prediction, the consistency of these models with A.1 and P.1 is highly doubtful. This is true even in the examples where the choice of the forecast is 'plausible' in the sense of D.1.

A different approach is adopted in what follows. The learning activity will be left implicit. At time t-1 the agent receives a signal, which is the input to her decision process; at time t she selects an action, the output y_t, according to some computationally viable algorithm. The algorithm is so conceived that the output is a differentiable function of the signal. The agent knows she is living in a large economy and her pay-off function. After resolution of uncertainty she comes to know the actual pay-off consequence of the output and can simultaneously compute, with the benefit of hindsight, the action which would have yielded the highest pay-off. This provides the decision taken at time t with a 'target' y_t^*, which is exogenous from the viewpoint of the decision maker, but endogenous from that of the modeller (it depends on the action taken by the representative agent). The algorithm is then adaptively revised, so that the action triggered by the same signal (received at t-1) would be changed in the direction of the 'target'.

Remark 4 : It is worth stressing that the 'target' y_t^* can not be interpreted as the optimal choice at t, since at this date the agent was facing strong uncertainty. y_t^* is the act at t which is optimal ex-post. This information is used, with pre-existing information on the pay-off consequences of 'similar' acts, to orient future decisions.

The decision algorithm applied in section 3 is a feedforward artificial neural network (ANN) with one hidden layer. Adaptation is implemented through the back-

[2] It may well be the case, for instance, that a specific prediction algorithm, though leading to a forecast error which is larger than the forecast error associated to a different algorithm, would have triggered an economic decision yielding a larger pay-off. The reason is that the pay-off function can be sensitive to the sign, as well as to the absolute size, of the prediction error.

propagation procedure. Both are briefly described in the sequel. For a more thorough presentation and discussion of these themes the reader is referred to Mehra and Wah, eds. (1992); Haykin (1994); Hertz, Krogh and Palmer (1991).

ANNs can be thought of as algorithms with an inner structure which is inspired by biological models of the brain functions. They reproduce, at least in part, fundamental properties of these models, and of human behaviour more generally. In particular: *(i)* composite information signals are processed in a parallel way; *(ii)* results are robust to lack of information, vaguely formulated problems, etc.

ANNs consist of simple, neuron-like processing elements called 'units'. These are normally arranged in different layers and interact using weighted connections (*fig.* 1). In feedforward networks information flows go from the input layer, which receives the *stimulus* of the external signals, to the output layer which gives the *answer*. Each unit has a state or activity level that is determined by the 'total input' received from other units in the network, or from an external signal, if the unit is in the input layer. This is conventionally identified here with layer 1. Total input received by unit k of layer K is typically a linear function of the inputs received by each unit j of layer J (just below K):

$$x_k = \sum_j y_j w_{kj} - \theta_k \qquad (1)$$

where y_j is the state of the jth unit and w_{kj} is the weight on the connection from unit j to unit k. Total input to unit k can also be affected by a threshold level θ_k.. This is not considered in what follows. The state y_j of a hidden or output unit j is normally a nonlinear bounded function of its total input x_j and can be discrete (with value 1 if total output is positive and 0 or -1 otherwise) or continuous. In the latter case the typical input output function is the sigmoid function:

$$y_j = \frac{c}{1+e^{-x_j}} \qquad (2)$$

where c is a constant, normally set equal to 1. The units in the first layer deserve a special treatment, since they do not receive inputs from other units. The number of

input units of a network can be conventionally identified with the (maximum) dimension of the vectors of external signals (input pattern). Each input unit receives an elementary signal (a scalar) and its state is the value of this signal.

The long-term knowledge of a connectionist network is encoded by where the connections are or by their weights (Hinton (1989)). Learning consists of changing the weights or adding or removing connections. The short-term knowledge of the network is instead normally encoded by the states of the units. A simple and widely used form of learning through changing weights is considered in what follows; it is known as back propagation (for an introduction to this procedure the reader is again referred to Haykin (1994), chapter 6).

Feed forward networks with (at least) one hidden layer are *universal approximators* in the sense that they can approximate any continuous multivariate function $f(\boldsymbol{x})$ to any desired degree of accuracy ε, provided that sufficiently many hidden units are available. This means that for each $\varepsilon > 0$ there exists a vector $\boldsymbol{w}$ of connection strengths such that the network output $F(\boldsymbol{x}, \boldsymbol{w})$ induced by the input $\boldsymbol{x}$ is a uniform ε approximation to $f(\boldsymbol{x})$: $|F(\boldsymbol{x}, \boldsymbol{w}) - f(\boldsymbol{x})| < \varepsilon$, uniformly on the domain of $f(\boldsymbol{x})$. It is a remarkable property of back propagation that the vector $\boldsymbol{w}$ exhibiting the above property can be learned by a multilayer feed forward network, if the net is trained with a sufficiently large number N of input vectors $\boldsymbol{x}_i$, $i = 1, \ldots N$, and their corresponding images $f(\boldsymbol{x}_i)$. Back propagation is not exempt from difficulties. In particular, the algorithm may converge to a local, rather than global minimum; in applications, however, poor local minima are rarely[3] encountered provided that the network has more units than are strictly required by the task (Hinton (1989)). A more serious difficulty is represented by the possibly-slow speed of convergence (Sutton (1986)). Despite these problems, the feedforward network with back-propagation learning offers a good (though perhaps not the best) example of a 'plausible' model of integrated decision making and learning.

Consider a feedforward network with one hidden layer, one single output unit (*fig.* 1) and continuous states determined by differentiable input-output functions. Suppose the problem is training the network to produce a desired response (state of

[3] There are applications, like pattern recognition, where local minima are not unfrequent (Gori and Tesi (1992)).

the output unit) for each member of a set of input vectors. Training takes place through a number of training cases. Let $\boldsymbol{x}_t$ be the input vector (composite external signal) which is fed into the network in case number t, d_t is the desired response or target and y_t the actual output. The square error at t is:

$$E_t = 1/2\ (y_t - d_t)^2 \qquad (3)$$

Consider the weight w_{kj} on the connection from unit j of layer J to unit k of layer $K = J+1$. The change in the weight w_{kj} occurring between the training cases t and $t+1$ is determined by the following rule:

$$\Delta w_{kj,t} = -\varepsilon(\partial E_t/\partial w_{kj,t}) \qquad (4)$$

If J is the hidden layer and K the output layer (with a single unit), the computation of $\partial E_t/\partial w_{kj,t}$ is accomplished by differentiation of (3) with respect to y_t, of y_t with respect to $x_{k,t}$ and of and (1) with respect to $w_{kj,t}$ (chain rule).

$$\partial E_t/\partial w_{kj,t} = (\partial E_t/\partial y_t)(\partial y_t/\partial x_{k,t})(\partial x_{k,t}/w_{kj,t}) = (y_t - d_t)\ (\partial y_t/\partial x_{k,t})\ y_{j,t} \qquad (5)$$

If J is the input layer, K the hidden layer, with $n > 1$ units, and H the output layer (with a single unit), the repeated application of the chain rule gets the desired result:

$$\partial E_t/\partial w_{kj,t} = (y_t - d_t)\ (\partial y_t/\partial x_{h,t})\ \ w_{hk,t}\ (\partial y_{k,t}/\partial x_{k,t})\ y_{j,t} \qquad (6)$$

Recall that the input-output (or input-activation) function is the identity for every unit of the input layer; if j is one of these units, then $y_{j,t} \equiv x_{j,t}$, where $x_{j,t}$ is an element of the input vector (external signal).

Learning by neural networks is usually studied by means of a two-stage procedure. The training session and the test session. The training session begins with initial connection strengths that are chosen at random on a given support. A set of input vectors, the training set, is passed through the network, yielding a final vector of connection strengths. In the test session this new vector is fixed (back propagation is

stopped) and the network ability to approximate desired responses on larger domains is checked. The application of the methodology just described to decision makers who live in a macroeconomic model, poses the following problems. In the first place, training is not carried out with samples of the 'true' target, because this is typically unknown and can be only approximated. Moreover, economic agents interact with the environment with the result that their approximations to the desired responses are not independent of their previous actions[4] (individual or, in any case, aggregate). This invalidates the universal approximator property of multilayer feed-forward networks. In the second place, the sharp separation between training set and test set conforms more to the needs of the cognitive scientist, who must run controlled experiments on the properties of ANNs, than to those of the economist who tries to mimic human decision making. Humans do not stop learning. Their training set is offered by experience, direct, or transferred from older generations. When they apply the knowledge so acquired, they do not stop revising it in the light of the observed results. Still, convergence to a 'correct' or approximated answer to a known problem posed in a new domain is likely to be substantially faster, after some training has taken place.

3. Procedural decision making in the overlapping generations model

The consumption-loan overlapping generations model (cf. Samuelson (1958), Gale (1973), Benhabib and Day (1982), Grandmont (1985)) has been extensively applied in the macroeconomic literature on learning; see for instance Grandmont (1985), Benassy and Blad (1989), Evans Honkapohja and Sargent (1993), Marcet and Sargent (1989*b*), Bullard (1994), Salmon (1995). As was just argued, P.1 does not hold in these applications (and in most studies of learning in a macroeconomic context). A variant of the familiar overlapping generations environment is considered also below and is complemented with a 'plausible' connectionist decision procedure.
With minor variations, the model building blocks are as in Bullard (1994) (see also Marcet and Sargent (1989*b*)). There is a large number of identical agents and a

[4] The approximated target introduced below is a heuristically transformed signal from the environment. In this respect it is similar to the *heuristic reinforcement signal* used in *reinforcement learning* (Haykin (1994), p. 61).

government. The agents live for two periods and are endowed with an amount of consumption good ω_0 when young and an amount ω_1 when old. Population is constant. Let c_0, c_1 and c_{min} denote consumption when young, consumption when old and 'subsistence' consumption, respectively. Since living is always preferred to dying, c_{min} imposes a lower bound on the voluntary choices on c_0 and c_1. Preferences over subjectively certain consumption bundles $(c_0(t), c_1(t+1))$, with c_0 and $c_1 \geq c_{min}$, are assumed to be represented by the separable utility function:

$$U(c_0(t), c_1(t+1)) = u(c_0(t)) + v(c_1(t+1))$$

It is worth stressing that consumers are not assumed to be expected utility maximizers. For ease of computation the utility function $U(c_0, c_1)$ is chosen to be linear in the level of consumption-when-old. In particular:

$$U(c_0, c_1) = [(c_0^{1-\alpha} - 1)/(1 - \alpha)] + c_1 \qquad 0 < \alpha \leq 1 \qquad (7)$$

In the limit case $\alpha \rightarrow 1$ (7) yields:

$$U(c_0, c_1) = log\,(c_0) + c_1 \qquad (7')$$

Government spending is financed by a positive flow of money supply. The stock of money supply is assumed to grow at the gross rate $m \geq 1$.
The nominal rate of interest is fixed at zero. For the sake of simplicity we assume $\omega_0 > c_{min}$, $\omega_1 = c_{min}$. Thus, the agent *never* wants to borrow when young. (If $\omega_1 > c_{min}$. she is prepared to borrow in her young age, provided that the perceived rate of inflation is sufficiently high.) In the monetary equilibria of this economy the money stock M_t is composed by the stock $(1/m)M_t = M_{t-1}$ in the hands of the old generation and by the quantity of money newly created by the government.
At the time of choosing her consumption when young, the representative agent born at time t can not observe the future equilibrium price p_{t+1}, indeed, she can not observe the equilibrium price p_t either. The reason is that the decision activity (which may involve

complex forecasts) is considered as non instantaneous and the equilibrium price p_t depends on $c_0(t)$.

Resolution of uncertainty occurs at the beginning of the old age, when the agent born at t comes to know the realized inflation rate (p_{t+1} / p_t), the welfare consequence of her actual choice $c_0(t)$ and, simultaneously, the action $c_0^*(t)$, which would have been occasioned by the (subjectively certain) anticipation of (p_{t+1} / p_t).

$$c_0^*(t) = (p_{t+1} / p_t)^{1/\alpha}, \text{ if } (p_{t+1} / p_t) \leq \omega_0^{\alpha}; \; c_0^*(t) = \omega_0 \text{ otherwise} \qquad (8)$$

Market clearing at time t requires:

$$\omega_0 - c_0(t) = M_t/p_t \equiv mM_{t-1}/p_t \qquad (9)$$

Market clearing at t and t-1 yields the true law of motion:

$$p_t = p_{t-1}\, m\, (\omega_0 - c_0(t\text{-}1))/(\omega_0 - c_0(t)) \qquad (10)$$

As is clear from (10), dynamic (equilibrium) paths which satisfy $c_0(t) = c_0(t\text{-}1)$ are monetary steady states of this economy, with $p_t/p_{t-1} = m$. If there is perfect foresight, and $p_{t+1}/p_t < \omega_0^{\alpha}$, then $c_0(t)$ is equal to $(p_{t+1}/p_t)^{1/\alpha}$; thus, the gross rate of inflation m defines a monetary steady state under such conditions, if $1 \leq m < \omega_0^{\alpha}$.

In Bullard (1994) the agent perceives the law of motion $p_t = p_{t-1}\,\beta$, but lacks the knowledge of the true value of β, the inflation rate in the economy. This is estimated through recursive O.L.S. and the decision on c_0 is taken as if the prediction on β is perceived as true. Bullard proves that there exists a critical value $m^0 < \omega_0^{\alpha}$ of the money growth, such that the monetary stationary state is locally stable if $1 < m < m^0$ and unstable if $\omega_0^{\alpha} > m > m^0$. The monetary stationary state undergoes a subcritical Hopf bifurcation when m goes through the critical value m^0. An unstable invariant closed curve exists near the stationary state for m less than but close to m^0, and coalesces to the stationary state at $m = m^0$ (cf. Bullard (1994), p. 476). It can be shown that m^0 is increasing in α on $0 < \alpha \leq 1$ and tends to 1 when α tends to 0.

A different approach is followed here. The agent's choice of c_0 is approximated through a feedforward network with two inputs, two hidden units and one output unit (see *fig.* 1). Initial connection strengths are chosen at random on the support consisting of the rational numbers[5] in the range $[-0.5, 0) \cup (0, 0.5]$[6]. Learning is introduced through the back-propagation procedure. At time t, the choice on $c_0(t)$ is determined by a forward pass through the network of the input pattern represented by the last observed inflation rate p_{t-1}/p_{t-2} and a scalar constant x. $c_0(t)$ is the state or activation level of the output unit at t. Market clearing determines p_t, hence p_t/p_{t-1}. Thus, the agent born at t-1 comes to know $c_0^*(t\text{-}1)$ and interprets it as the 'target' of her decision at t-1.

$$E_{t-1} = 1/2\, (c_0(t\text{-}1) - c_0^*(t\text{-}1))^2$$

With this knowledge, she computes (through back propagation) the connection strengths to be used in the choice of $c_0(t+1)$ and delivers this instruction to the future generation of the family. Economic considerations suggest that the constant c in the sigmoid input-output function (2) takes the value ω_0. This fits with the assumption that the young agent is never prepared to consume more than her endowment ω_0.

The dynamic behaviour of the above model economy was simulated on a P.C. by means of the DMC software (Gallo (1992)). The analysis is oriented to the comparative evaluation of the convergence properties under connectionist decision making and under O.L.S. learning. The gross rate of money growth m is shown to have a crucial role in this respect. The endowments are held constant throughout the simulations ($\omega_0 = 2$, $\omega_1 = 1.8$). m is constrained to belong to the open interval $(1, \omega_0^{\alpha})$ which represents the range of m values which can support a monetary perfect-foresight steady state with inflation. The adjustment parameter ε of equation (4) (ε rules the sensitivity of connection strengths with respect to perceived errors) and the constant x in the input vector are understood to be unchanged throughout ($\varepsilon = 0.2$, $x = 1.5$). The main findings are summarized by the following facts.

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[5] Irrational initial conditions can be only approximated in computer simulations.

[6] Obviously enough, connection srengths may well exit the interval [- 0.5, 0.5], after some learning has taken place.

Fact 1

Asymptotic convergence to the (perfect-foresight) monetary steady state obtains for $1 < m < m^0$ under O.L.S. learning and over the whole range $1 < m < \omega_0^{\alpha}$ under connectionist decision making and learning. The convergence properties of the economy adopting the neural-network procedure are therefore remarkably stronger. For instance, in the limit case $\alpha = 1$ easy computations yield $m^0 \approx 1.366$ and $\omega_0^{\alpha} = 2$. m^0 is the m value in the interval $[1, \omega_0^{\alpha}]$ giving rise to a root of unit modulus in the characteristic polynomial associated to the local dynamics under O.L.S. learning. Convergence of the consumption and inflation variables to their steady-state values can be accomplished through a convergence of one or more couples of connection strengths to orbits of period 2.

Table 1

α	ω_0^{α}	m^0
1	2	1.36603
0.5	1.4142	1.1547
0.25	1.1892	1.04538

Superior extrema, for alternative values of the preference parameter α, of the gross rates of money growth yielding convergence to the monetary steady state under back propagation (ω_0^{α}) and O.L.S. learning (m^0).

Fact 2

In the range of m values ($m < m_0$) on which convergence obtains also with the O.L.S. procedure, the transition 'time' (order of magnitude of the number of iterations) is moderately higher under back propagation[7].

[7] This result refers to economies with the utility function (7'); its extension to larger domains has not been investigated. The two procedures start with a similar amount of inherited knowledge about inflation.

Fact 3

For sufficiently high rates of money growth the convergence of back-propagation learning does not scale satisfactorily with 'time'. The transition to highly inflationary steady states requires a lapse of 'time' of the order of thousands of iterations. If initial connections are random, the choice of initial conditions on c_0 and inflation in a neighbourhood of the steady state may not be conducive to faster convergence. (In the beginning of the transition, random connections would generally move c_0 away from its steady state value.) Conversely, a long training of the network with inputs generated by the ongoing rate of money growth m does not guarantee a fast return to the steady state (corresponding to m) after a large shock to c_0. The time scaling of back-propagation convergence is affected by a change of the utility function, since a corresponding change is produced in the error surface. This is the graph of the function which gives the error E (see (3) above) as a function of the connection strengths (for a given input vector).

Table 2

m	back prop., random w	back prop., trained w	O.L.S.
1.05	10^3	10^3	10^3
1.2	10^3		10^2
1.3	10^3		10^2
1.4	10^3	10^3	
1.6	10^3		
1.8	10^3		
1.9	10^4		
1.98	10^5	10^5	

Time scaling of convergence: lowest upper bound, in powers of 10, to the number of iterations required by convergence. The above data refer to the parametric case $\alpha = 1$, and fixed initial conditions $c_0(t\text{-}1) = 1.2$, $p_{t-1}/p_{t-2} = 1.6$ and $p_{t-2}/p_{t-3} = 1.6$. The training of w refers to an environment with the relevant rate of money growth.

Conclusions

The above facts suggest two related remarks, which give also a direction for further work.

The first remark is that the perception of uncertainty, or of the possibility of ignorance, strengthens the convergence (non explosive) properties of economic trajectories, to the extent that it leads to decision and learning rules which are robust to poor information. The same indication is offered by Salmon (1995), which studies the effects of neural-network learning (but not decision making) in a variant of the overlapping-generations inflationary economy considered above. In that paper, however, the rate of money growth is not exogenous, a simultaneity problem arises in the determination of $p(t)$ and $c_0(t)$ and (partly because of this) network learning is implemented in a different way. These differences explain the fact that learning does not converge to perfect foresight in Salmon's paper. Still, convergence properties are again definitely stronger under connectionist than under O.L.S. learning.

Grandmont and Laroque (1989) and Grandmont (1994) suggest that agents faced with strong uncertainty are prepared to extrapolate a large number of dynamical behaviours. (This premise is critically considered in Caminati (1995).) They show that in this case a stationary temporary equilibrium is likely to be locally unstable under learning. Fuchs (1979) studies the problem of whether or not error learning behaviour is stabilizing. The author reaches a negative conclusion on this point, but admits that the conclusion can be invalidated by the case of very careful behaviour. Careful behaviour as defined in Fuchs (1979) imposes very strong conditions on adjustment speeds and therefore can be regarded as exceptional by the author. Salmon (1995) identifies careful behaviour with behaviour robust to poor information and mimics it through connectionist learning. Connectionist decision making and learning are simultaneously considered in the present paper. The process provides an example of 'plausible' behaviour in situations where agents have at least some perception of their ignorance. The findings, summarized by Facts 1-3, are similar, in spirit, to those obtained by

different implementations of 'plausible' decision making in environments with endogenous uncertainty[8]. These results show that there are relevant (non exceptional) forms of learning that are stabilizing. They suggest the opportunity of reconsidering the relation between lack of information, modes of learning and the qualitative properties of economic trajectories.

The second remark is that, in so far as the rate of convergence can be very slow (see Fact 3) the stated weaknesses of back propagation are confirmed by our results. Thus, a first direction for further work is offered by the incorporation of methods which are known to accelerate back-propagation convergence[9]. Still, it is worth stressing that applications of back-propagation learning in macroeconomics present non-standard features because economic agents do not track down an exogenous target, but interact with their environment. In this respect the above application shares features with a different approach, which is known in the connectionist literature under the label of *reinforcement learning*. Here the learning system observes states of the environment and performs actions affecting future states and also inducing performance signals (*reinforcement signals*) which are used to evaluate the pay-off consequences of these actions. The problem is one of learning (some appropriate transformation of) the map from states and actions to reinforcement signals. This approach should be of interest to economists, because it lends itself to a modelling of the self-referential aspects of decision making and learning in the social sciences.

[8] An example which makes use of genetic algorithms in the context of a cobweb model is Arifovic (1994). See also the references quoted therein.

[9] Cf. Haykin (1994), pp. 192-205.

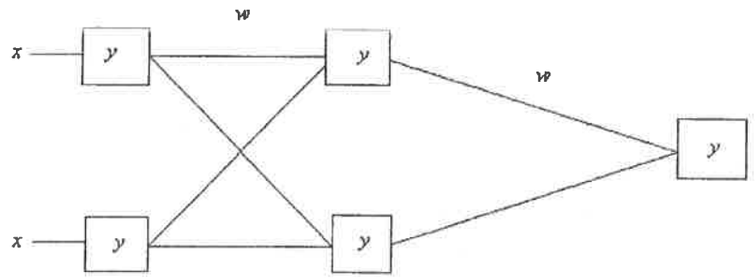

fig. 1

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