Evaluating Competitive Strategies

Scott Moss,
Director, Economic and Business Complexity Research Centre
Manchester Metropolitan University

Professor Huw David Dixon,
Professor of Economics
University of York
and
Visiting Professor
Economic and Business Complexity Research Centre
Manchester Metropolitan University

Steven Wallis,
Economic and Business Complexity Research Centre
Manchester Metropolitan University

Abstract

In this paper we introduce a conception of learning which is a natural extension of economists' representations of learning and which is natural to develop using KBS technology. In the particular form of KBS we use, rule conditions and actions are well formulated formulae of first-order predicate logic (FOPL). As a result, the simulation results obtained from these models are no less analytical than those of pure analytic models. Our results are further strengthened by an experimental design for simulations of competitive behaviour which eliminates implicit bias in the selection of possible behaviours. The system is applied to the Cournot duopoly model. We find that modest intelligence on the part of at least one duopolist systematically increases the profits of both.

Keywords: ARTIFICIAL INTELLIGENCE, LEARNING, SIMULATION, GAME THEORY, COMPETITION

1 Introduction

Economists typically model interactions of competitive strategies as mathematical games. Reaction functions or parameterized constrained optimization problems are assigned to model firms by the modeler. Each firm observes the actions of competing firms and responds mechanically. The strategies and, hence, their responses are whatever seems plausible to the model builders. There is no scope for firms to change their strategies in response to poor competitive performance though, in some cases, strategies are chosen by agents at random from a predetermined menu.

In the real world, successful organizations are flexible. Their aspirations go up and down in response to the extent of their realized successes. Their strategies change in the light of growing experience and environmental changes.[1] In general, strategies do not evolve as menu selections but, rather, as the consequence of a changing understanding of the economic environment.

In this paper, we argue that a more realistic but still rigorous analysis of the evolution of competitive strategies is well within our grasp. What is more, this more realistic analysis can yield systematically better results than game theoretic analyses. That is, agents which evolve their strategies within a competitive environment "do better" than firms which stick with any arbitrary game theoretic strategy where by "do better" we mean that when they have the same target variable(s) as game-theoretic agents, they achieve higher values of those variables.

We thus have two closely related purposes in this paper. One is to demonstrate a rigorous but realistic approach to the modelling of the evolution of strategies; the other is to compare that approach with the standard game theoretic approach to the evaluation of competitive strategies.

Our procedure here is systematically to generate a population of game-theoretic strategies which are assigned to simulated firms. The firm-assigned strategies then play a round-robin tournament. That is, each strategy is played once against itself and every other strategy. Each game is independent of every other game so that there is no inter-game learning. A second set of strategies is initially identical to the strategies gener-

[1] So much has been well accepted by students of organizational change since Marshall (1919) in economics (though later economists have forgotten this), Cyert and March (1963) and, in business history, Chandler (1962, 1977) and Penrose (1956). There are of course substantial bodies of literature which have developed from each of these seminal works.

ated in the manner suggested above but they are all augmented by the same learning procedure. The firms assigned a learning-augmented strategy begin each game with the basic strategy but modify it according to their experiences within the game.

The profits attributable to each strategy in each game is collected and used to assess its relative goodness. Two means are used. One is simply to compare the average profits of each strategy. The other, which is arguably more robust, is to use the individual results from all of the games to simulate a pseudo-evolutionary processes due to Axelrod (1990).

2 A New Approach to the Modelling of Learning by Economic Agents

Conventionally, economists model learning by agents as a process of estimating the parameters of the "correct" model of their economic environment: the market or the whole economy. This is what is involved in least-squares learning, in rational expectations models, in consistent-expectations models and in Bayesian models.[2] The presumption must be that agents have whatever computational and information-processing resources are required in order to specify and then estimate the "correct" model.

The essence of bounded rationality is that agents' computational and information-processing capacities are limited. Boundedly rational agents must therefore adopt strategies for losing irrelevant information so that it is not processed and is not used in computing actions or expectations. This is surely one use of models. Applying a particular model entails the acquisition and processing of the information used by that model rather than some random selection of information. The model also determines the computations to be performed with that information in order to determine the outputs from the model. Such outputs can be more information processed to feed into further computations or they can be indications of actions to be undertaken. In analyses of the behaviour of boundedly rational agents, therefore, the model seems an appropriate metaphor for the process of filtering information and undertaking limited computation.

By model, we mean a logical (possibly mathematical) relation. Models have arguments (or inputs) and results (or outputs). In this paper we represent learning as a pro-

[2]Learning by doing is different in that agents do not even estimate anything. They simply reduce their marginal inputs to achieve a given output according to an exogenous function of cumulative output.

cess of developing models by means of the selection of inputs or changes in the assumed relationship between model inputs and outputs.

Since models enable agents to lose information in order to keep information processing and computation within manageable bounds, we have to describe information-losing practices. The main such practice which we capture in this paper is the reduction in the dimensionality of the information used to calculate the appropriate actions of the agent. In fact, dimensionality-reduction is a very common practice, as we shall now see.

Price, for example, has the dimensions of $\frac{money}{good}$. Output has the dimensions of $\frac{good}{time}$. Their product, sales, has the dimensions of $\frac{money}{good} \times \frac{good}{time} = \frac{money}{time}$. It has the further virtue that, by eliminating the *goods* dimension, the sales of any one product can be and commonly is added to the sales of other products. Thus, reducing the dimensionality of variables has the effect of reducing the number of variables that agents have to consider by creating summary variables while generating variables that can be added together, thus further reducing the number of individual variables to be taken explicitly into account.

Information available to any agent is stored on a public database maintained by the simulation environment. In a model of competitive processes, the environment is the market. Information or propositions which are known only to individual agents are stored on databases accessable only by the agent. This makes it possible for us to assume in this paper that the model developed by one duopolist will not be known to the other.

In the model reported here, learning takes the following form:

1) In period 1 of a game, the intelligent firms formulate all dimension-reducing variables they can from the raw data available to them. In a simple Cournot game, the raw data is their observations of market price, the vector of outputs and their own profits. Agents know the dimensions of price, output and profit. They have rules which indicate conditions in which to form the ratios and the products of variables. As a result, they define sales, the profit margin (the ratio of profit to price) or its inverse and profit per unit of output or its inverse. They also recognize the ratios of their own decision and target variables to the corresponding variables of their rivals.

2) At each period, the latest values of the reduced-dimension variables are calculated and stored on the agent's database.
3) When one or more target variables fall in value from one period to the next, the agent evaluates the series of variable values to find pairs of series which are related either inversely or directly. The criterion for a direct relationship is that from one period to the next three times as many movements of the variables were in the same direction as in the opposite. The criterion for an inverse relationship is that three times as many movements were in opposite directions as in the same direction. In determining the presence of an inverse or direct relationship, only the preceding five observations are taken into account.
4) If the agent finds an inverse relationship between a decision variable and a target variable it then looks for relationships between one of the constructed intermediate variables and the target and decision variables, respectively. If these are of opposite direction, this confirms the inverse relationship by providing a confirmatory simple model. The relationships thus found are also available for use in the construction of relationships among other variables. That is, when there are several decision variables and a known relationship between a target and a constructed intermediate variable, then it is necessary only to look for a relationship between that intermediate variable and a decision variable.
5) If no direct or inverse relationships are identified, the agents look for lagged inverse or direct relationships. As only one-period lags are permitted in the reaction functions, only one-period lags are assessed in the search for relationships among the variables.

The mapping from model to action is clear. If the model implies an inverse relation between decision variable and target variable, reduce the value of the decision variable. If a direct relation is implied, increase the value of the decision variable.

3 Knowledge Representation and Organization.

The simulation model for the experiments reported here was implemented in SDML, a modelling language based on a knowledge-based system (KBS) which has very strong logical properties discussed in section x below. The agent’s modelling procedures are described by rules in a high-level rulebase while the actions to be taken in any given set of conditions are described by rules in a low-level rulebase. In general, the high-level rulebase is a meta-level rulebase which evaluates the effectiveness of the action (low-level) rules and, on the basis of that evaluation, can modify, delete and replace them. In the present case, meta-level rules are used to respecify the agents' models when their predictions imply actions which reduce the values of the target variables. There are other rules to map the model results into the contingent action rules of the agents. These contingent action rules are written by meta-rules onto the low-level rulebase. Because the rules on this low-level rulebase deal with the objects of the models such as outputs and prices, they are called object-level rules and the low-level rulebase is the object-level rulebase.

Figure 1 describes the organization of knowledge implied by this distinction between meta-level and object-level rules as well as the flows of information required by our representation of learning as modelling. The modelling procedures described in section 2 are represented by the box at the upper left of the shaded area. The agent remembers both events and his internal models. Events perceived in the environment can lead to the invocation of the modelling procedures and, therefore, revisions of existing models. Model results map into actions as already explained.

The agent's modelling procedures are represented as meta-level rules. These determine any changes in the agent's current model of the effects of his own behaviour on his target variables. The current model is then stored on a database attached to the meta-level rulebase. This database can only be accessed by the meta-level rulebase.

The decoding process from internal model to action can take one of two forms. Either it can write statements to a database accessible by the object-level rules and these statements then enable object-level rules to fire or it can write object-level rules. In either case, the decoding process is implemented as a subset of the meta-level rules. In the experiments reported here, the meta-level rules asserted clauses to the object-level database which parameterized the action rules on the object-level rulebase.

Figure 1 near here

Normally, the agent would assert to his object-level database a note of intended actions. Since he may not be able to realize those intended actions (for example because there is insufficient demand for the goods he supplies), the intension to act is signalled to the environment which resolves all intended actions of all agents and makes known the consequences of their intensions. An excess supply, for example, will result in a realized but unintended increase in inventories. Publicly known events are recorded on a public database which is attached to the environment. This database can be accessed by all meta-level and object level rulebases. Statements asserted to the object-level and meta-level databases are known only to the agents who respectively own them. We also do not allow object-level rulebases to access the corresponding meta-level database on the grounds that we do not believe that individuals making routine decisions within organizations have access to the information required to make the strategic decisions.

4 A Tournament: The Game

At such an early stage in the development of our procedures of modelling decision-making and learning in complex environments, it seems sensible to make clean comparisons among our modelling techniques and the standard means of formal evaluations of competitive strategies. Clean comparisons seem best made in simple, highly controlled settings.

An appropriate model to use for this comparison is the standard, textbook Cournot model.[3] We therefore set up a tournament among Cournot strategies. The tournament comprises games amongst pairs of strategies. The standard players (here called dumb firms) have reaction functions of the form

$$(1) \qquad x_i(t) = \max[h_{i0} + h_{i1} \cdot x_j(t-1), 0]$$

where $x_k(t)$ is the output of the kth firm at period t. Each firm determines its current non-negative output on the basis of its rival's output in the preceding period.
The price at each period is determined by an inverse demand function, in this case

$$(2) \qquad p(t) = \max[1 - \sum_k x_k(t), 0]$$

where $p(t)$ is the price at period t which cannot be negative.

It is conventional in this literature to assume that firms face constant variable costs. For our purposes, the particular level of the constant variable costs makes no difference and, so, is most conveniently set to zero. Thus, the profits of the kth firm at period t will be $p(t) \cdot x_k(t)$.

We want here to test our ideas against the best that conventional economic analysis has to offer. Within the Cournot framework, therefore, we want to play smart (*i.e.* learning) firms against dumb firms with the best possible reaction functions.

Several papers in the economics literature have looked at formal games in which firms choose reaction functions or supply functions in a static framework (Hart (1985),

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[3]In this model, each of the two competitors sets his output as a response to the previous output of his rival. The function describing this behaviour is the reaction function.

Meyer and Klemperer (1989)), or in a repeated framework with no discounting (Stanford (1986)) which is more or less equivalent. The idea is that firms choose a reaction function (or supply function), and their payoff is determined by the market outcome generated by the chosen reaction function (the intersection of reaction functions or market clearing price).

A Nash equilibrium in reaction functions is (in the case of duopoly) a pair of reaction functions and a pair of outputs such that: the outputs represent market outcomes given the reaction functions; each reaction function is optimal given the other (i.e. neither firm can increase its profits by changing its reaction function). In these papers is the informal “Folk” result that any pair of strictly positive outputs which yields non-negative profits can be supported as an equilibrium in reaction functions. However, none of these papers is able to provide a specific algorithm for generating equilibrium reaction functions. In Dixon (1992), a simple algorithm is provided which is able to specify the unique linear reaction functions and supply functions that constitute an equilibrium pair corresponding to any equilibrium point. The method is both very simple and it yields a population of reaction functions which are compatible with Nash equilibrium. A Nash equilibrium is one on which the rival firms cannot improve. This is the best outcome which economic analysis offers.

Given equations (1) and (2), we can take any point in the set *A* (see Figure 2) where total output is no greater than unity, and both outputs are strictly positive and calculate the equilibrium linear reaction functions from the tangencies to the isoprofit functions at that point.

If we take a point *x* in the interior of *A*, we can map out the isoprofit curves for firms 1 and 2. Let firm 1's reaction function *R1* be the tangent to firm 2's isoprofit curve *IP2* at the point *x*. Now, firm 2 is able to vary its own reaction function to ensure that it intersects uniquely at any point on firm 1's reaction function *R1*. However, since *R1* is a tangent to *IP2* at *x*, the profits for firm 2 are lower at all points other than *x* (so long as firm 2's upper-contour set is strictly convex as depicted). Hence firm 2 can do no better than choose a reaction function which goes through *x*. Likewise, firm 2 can choose *R2* which is tangent to firm 1's isoprofit curve at *x*. This pair of reaction functions intersect at point *x* and constitute optimal responses to each other.

Figure 2
near here

We have used this algorithm to generate a tournament. We undertake a grid search of the set A, and at each point we calculate the tangent to firm 1's isoprofit curve. Since the model is symmetric there is no loss of generality in calculating only one firm's reaction function. The formulae for the intercept and slope, respectively, of the reaction function are

$$h_{10} = 2x_1 + 2x_2 - 1 \tag{3}$$

$$h_{11} = \frac{1 - (2x_1 - x_2)}{x_1}. \tag{4}$$

We claim three advantages from generating the candidates for the tournament in this way. First, it is an appropriate way of generating linear reaction functions: every one is a possible equilibrium decision rule in a conventional duopoly model. Second, it guarantees that the reaction function passes through the relevant portion of output space. Finally, by generating reaction functions uniformly over a grid we avoid any possibility of bias in the selection of candidates for the tournament.

5 A Tournament: The Set-up.

As a test of the procedures described above, we ran a tournament involving 18 firms. These firms were generated by taking a grid of points within the triangle *A* of Figure 2. The granularity of this grid was 0.18. That is, starting at point (0.18, 0.18), the optimal reaction function of the firm whose output is represented on the horizontal axis was calculated. The system then shifted 0.18 units to the right. It first determined whether it was in A by calculating the price corresponding to that pair of outputs. If the price was positive, it calculated the next optimal reaction function. If negative, it shifted up 0.18 units and then to the left until positive profits were found. Optimal reaction functions were then computed for each point 0.18 units to the left until either price or an output were negative in which case, the system shifted up and started moving to the right again. The grid search halted when the value of output measured on the vertical axis exceeded 1.

With a granularity of 0.18, nine firms were generated. The reaction-function slopes and intercepts for each firm are reported in Table 1. For each firm, these parameters of its reaction function were stored on its permanent private database as two clauses: “reactionFunctionSlope *s*” and “reactionFunctionIntercept *i*” where *s* and *i* were the slope and intercept values calculated from the grid search. Each firm also had two object level rules. One to set the initial output and the other a declarative statement to calculate the current output from *s*, *i* and the previous output of the rival. None of these nine firms had any meta-level rules and so none could alter its strategy by observation and learningFor each of these firms, a copy was made to which was added a set of meta-level rules which collectively described the learning procedure outlined in Section 2 above.

The 18 firms generated in this way were the templates from which the firms in the tournament were copied. Copies of each of these templates played one game against a copy of itself and one game against a copy of each of the other firm templates. The total number of games in the tournament was 171.

Table 1
near here

If both players were dumb, the game stopped when an output cycle was repeated. Cycles could be of length 1 (each player's output was the same as in the previous period) or of length 2 (each player's output was the same as in the previous period but one). Since the reaction functions entailed only one-period lags, cycles of greater length are not possible.

If one or both of the players was smart or if no cycles were identified the game lasted for 12 periods. The presence of at least one smart player in a game opened up the possibility that it would collect data over several periods before changing its output or reaction function. Consequently, a cycle might be (and, in these circumstances, often was) short-lived.

Though the raw data from each game is kept, the summary data used in analyzing the results was the average profit of each of the firms in the game.

This setup entails two important design issues. One is the default game length and the other is the firms' initial outputs.

In games between dumb firms, some will end in equilibrium cycles (of one or two periods) and this is in practice always achieved within 12 periods. Some games among dumb firms are unstable in that either the sum of the outputs is greater than one or the outputs are non-positive. Either way, both firms will end up with zero profits because either price or output is zero. Finally, in preliminary runs of the tournaments, we found that a default game length of 12 periods yielded results that were not different from the results obtained with 10-period default games when the average profit collected was the average of profits over the last five periods of any game that did not cycle. There were, however, some differences relative to eight-period default games.

In this tournament, the initial output associated with each reaction function was the value of x_1 used to generate its slope and intercept. We have found in later and much larger scale experiments (without learning firms) that the choice of initial output can make a statistically significant difference to the outcome of the experiment. However, though the best strategies may differ slightly (though still significantly), the goodness of the best strategies does not vary significantly. Moreover, with the coarseness of the granularity of the grid used here, the starting values are irrelevant.

6 The Tournament Results.

The data captured from the tournament was the average profit obtained for each strategy in each of its games. With 18 strategies, this amounts to ${}_{18}C_2$ (= 153) games and numbers.

Our interest here is not in just the average profits made by each strategy in a game or in the whole tournament. We want to determine which strategies are robustly the best in the sense that they would do relatively well against any other strategies. For this reason, we assessed the relative performances of the individual reaction functions — both standard and learning-augmented — by means of the following algorithm inspired by Axelrod (1990):

1) Assign to each of the n firms at round 0 a proportion $z_{i0} = 1/n$ (i = 1...n) of a notional population of such firms.
2) Increment the round.
3) Calculate the fitness of all firms i at round t as

Figure 3 near here

$$z_{it} = z_{i,t-1} + e\left[\frac{\bar{\pi}_{it} - \bar{\pi}_t}{\bar{\pi}_t}\right]$$

   where $\bar{\pi}_{it}$ is the average profit of surviving firm i in all tournament games played against surviving firms and $\bar{\pi}_t$ is the average profit of all surviving firms.[4]
4) Eliminate any firm i such that $z_{it} \leq 0$.
5) Normalize the fitnesses of the firms so that $\sum_i z_{it} = 1$.
6) If, for any firm i, $z_{it} \neq z_{i,t-1}$, then go to step 2.
7) Halt.

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[4]This differs from Axelrod's evolution equation which, we intuit from his text (pp. 49-51), is

$$z_{it} = \frac{\bar{\pi}_{it}}{\sum_j \bar{\pi}_{jt}}.$$

The results obtained from the tournament reported here provide strong confirmation of the different nature of average profits from our pseudo-evolutionary outcome as measures of strategic strength. If we take the average profits of each firm in all games, the results are as indicated in Table 2. It will be noted that the most profitable firm on average was Firm-5 while the least profitable firm on average was Smart-Firm-6. If, however, we use the pseudo-evolutionary mechanism, then Firm-5 can barely survive if the strength of the evolutionary mechanism is very weak and otherwise falls to the smart firms. This result is reported in Table 3.

The superficial reason for the greater success of the smart firms under rigorous selection regimes can be seen in Figure 3. We note that, although Firm-5 has the highest average profits of all firms, it falls in the middle of the range of all firms' rivals' profits. What is happening here is that Firm-5 does extremely well relative to some of its rivals, principally other dumb firms whose own average profits are very low. When those dumb firms are eliminated, the games in which Firm-5 generated its highest relative average profits are also eliminated.

Table 2 near here

Consider, for example, the games between Firm-5 and, respectively, Firm-3 and Smart-Firm-3. The profit series for these games are depicted in Figure 4 and Figure 5. In fact, Firm-3 had average profits over the game of 0.025 while Firm-5's game average profits were 0.011. When Firm-5 played Smart-Firm-3, however, its average profits in that game were 0.056 as against 0.068 for Smart-Firm-3. This kind of result was the norm in games between smart and dumb firms. The smart firms soon worked out that lower outputs yielded higher profits. As a result, they lowered their outputs (by reducing their reaction-function intercepts and setting the slope to 0) while the dumb firms waited one period and then raised or lowered their outputs according to their reaction functions. In that first period, at least, the dumb firms enjoyed an increase in profits due to the higher price without, in general, having lowered their outputs. The smart firm's intelligent output reduction benefited both firms, but benefited the dumb firm most.

Table 3 near here

Figures 4 & 5 near here

The smart firms did better overall because the average profits in games with at least one smart firm playing were higher than the average profits in games against dumb firms. Our conclusion here must be that a modicum of intelligence benefits all competitors - whether dumb or smart - in Cournot duopoly games.

7 The Simulation Platform Imposes Logical Consistency

The simulation model and experiments reported above were implemented in SDML, a logic programming language developed at the Centre for Policy Modelling at Manchester Metropolitan University. SDML provides facilities for the creation and manipulation of rulebases and databases and ensures that, within any rulebase, the rules are logically consistent.

SDML stands for **s**trictly **d**eclarative **m**odelling **l**anguage. A declarative language differs from an imperative language such as C, Pascal or Fortran in that there are no instructions to the computer to perform actions. Instead, results are declared to be true either by assumption or as a result of having been proved true within some logical system. In the experiments reported here, each game began with the declaration of the two firms with their reaction functions and (if smart) their metarules for changing their reaction functions. The characteristics of the duopoly market, including the inverse demand function, were also declared in advance of the game. Further declarations determining each rival's output, the market price and agent models, etc. were deduced by the instantiation of rules.

Because SDML is a rich language with a large number of facilities, it is appropriate here to concentrate on the most relevant aspects of the language and its formal properties as they impinge on the modelling of learning-as-modelling.

In SDML, every instance of rule that can be fired is fired. This is different from most knowledge-based systems (KBSs) since, generally, all rule instances that can be fired are identified and then, in the process of conflict resolution, one of them is chosen according to some criteria. That rule instance is fired and, where necessary because of consequent changes in the environment, a new set of rule instances is identified and one chosen to be fired, and so on until no new rule instances can be identified. In essence, SDML does not seek to resolve conflicts. This imposes a certain discipline on the modeller since, for example, it will not generally be appropriate to have two rule instances fired in the same period such that each sets a price of the same product. Rules must be written carefully to avoid inappropriately multiple values of any variable.

Partly on grounds of efficiency and partly to elucidate the structure of the models comprising initial declarations and rules, SDML calculates for each rulebase a dependency (possibly cyclical) digraph. The root and the end of the dependency graph for the smart Cournot duopolists’ meta-level rulebase is exhibited in Figure 6(a) and Figure 6(b).

We define rule *R* as a *dependent* of rule *S* if and only if a clause in the actions of *S* unifies with a clause in the conditions of *R*. If *S* fires, it may cause *R* to fire, which may cause *R*'s dependents to fire, and so on. The dependency graph is obtained by calculating all dependencies between rules in a rulebase. In Figure 6(a), for example, there are three rules which are not dependent on any other rule. These have the titles *set up targets and decision variables*, *endorsement — rule firing*, *model rival behaviour — endorse confirmed reaction function* and *dimensions*.

The links emanating to the right from the nodes representing those rules are the dependency links.

The rule partition including *model rival behaviour — reestimate reaction function* and *model rival behaviour — restate confirmed reaction function* is dependent on both *endorsement — rule firing* and *model rival behaviour — endorse confirmed reaction function*. In SDML, every possible instance of the four rules which are not dependents will be fired first and then SDML checks to see whether the dependent rules can be instantiated and fired. Once all of the rules in every partition on which the next partition depends have had rule instances fired, SDML instantiates and fires the rules in the next partition.

Figure 6(a) and 6(b) near here

That dependency networks can exhibit cyclicality is evident from Figure 6(b) which depicts the right-most partition of the dependency graph. That the partition is itself dependent upon a large number of other rules is evident from the number of links entering it from the left. In addition, three links emanate from the right side of that partition. Two of these disappear back to the left indicating that there are other rules which depend on the rules in this partition and on which the rules in this partition directly or indirectly depend. As we will see, at least one of the rules in the partition in Figure 6(b) declares the existence of a model and, at the same time, requires the existence of a model to instantiate its conditions. The models must be different but SDML cannot identify this difference. As a result, SDML calculates that the rule is dependent upon itself.

In order to enable the modeller to maintain logical rigour in his models, we have developed SDML to mimic first-order logics in ensuring that the order in which rules are fired will not affect the state of the world after all rules have been fired. This is achieved by a mechanism relying on assumptions.

An example of the use of assumptions arises when a rule only fires if a condition is not true. For example, a rule with condition **not c** and action **a** fires if clause **c** is not in the database. This rule states that **a** is true if **c** is not known to be true.

The implementation ensures that if **c** is found to be true, by being asserted to the database by another rule before or after this rule is fired, then **a** is not concluded to be true. When this rule is fired, **a** is concluded under the *assumption* that **not c** is true, and asserted to the database with a *tag* indicating this assumption. If further clauses are deduced to be true on the basis that **a** is true, due to other rules firing, then they are also tagged with this assumption. Thus, assumptions are combined and propagated as rule firing proceeds. The system detects contradictions among assumptions, and impossible combinations of assumptions are eliminated.

After firing the rules, the assumptions are resolved in order to determine which assumptions are true and which are false. After assumption resolution, all clauses tagged with false assumptions are retracted from the database, and all clauses tagged with true assumptions are tagged as definitely true.

If the rulebase is partitioned as described above, then no rule in an earlier partition can be affected by a rule in a later partition. Therefore, assumptions can be safely resolved for every partition in turn, after firing the rules in it. The order in which rules are fired still does not affect the final state of the database.

In Figure 7, we reproduce from an SDML rule-editing window the rule *model building - forecasting rival behaviour* from the partition in Figure 6(b). The top pane of that window contains a comment describing the rule in more detail than its mnemonic title. The middle pane contains the conditions of the rule and the lower pane the action (*i.e.* the clause which is to be declared if the rule fires). Subclauses are separated by ‘\’ and sub-subclauses by ‘|’. Thereafter, further nestings of clauses are separated by alternations between ‘\’ and ‘|’.

The first subclause of the conditions clause states that the duopolist has previously declared a belief about some agent and that belief is that in a specified set of conditions the agent will perform a specified set of actions. The second and third clauses state that the agent about whom this belief has been declared is a firm but is not the agent using the rule. The next two clauses (beginning “productOf”) obtain the duopolists’ respective products.

Figure 7 near here

The subclause “clauseList ?believedConds and ?believedCondsList” is a special kind of clause. The first word in every clause is a keyword. SDML keeps track of all possible keywords and the syntax associated with each. Some can be asserted only to public databases, some only to object-level databases and some only to meta-level databases. All clauses with the *clauseList* keyword take three arguments: a clause, a symbol and a list. The list, the clause or the symbol or some combination thereof must be instantiated. If the list and the symbol are instantiated, then SDML instantiates the pattern variable in the place of the clause with a clause starting with the symbol as keyword and each element in the list as a subclause. If the clause is instantiated, then SDML instantiates the symbol with the keyword of the clause and the list with a list of the subclauses.

The reason for this is that lists are not logical clauses but they are easier to modify. This is seen from the next few subclauses. Having constructed ?believedCondsList from the clauses to which ?believedConds has been instantiated, the rule then checks to see if that list includes the lagged clause “valueOf ?var ?ownProduct ?ownVarValue” and, if it does, removes that clause from the list of clauses in ?believedCondsList.

There then follows a disjunctive clause looking in much the same way at the believed actions. The disjuncts allow for the actions to be represented by a conjunctive clause or by a single clause without subclauses. Either way, the issue is whether the rival firm declares the current value of his decision variable as a response to some lagged value of the agent using this rule.

The next four clauses in the conditions of this rule determine that the agent has already specified a model in which the variable in question is determined in the market directly by the value of the corresponding decision variable. In the Cournot model, for example, supply determines sales exactly. In other models, the relationship is more complex and requires the specification of a more elaborate relation between decision variable and market variable.

As specified here, a model is always a list of clauses which have variables to be determined by the model (the dependent clauses list), a list of instantiated clauses (the dependent clauses list) which are in effect the arguments of the relation, and the clauses which, given the variables instantiated in the independent clauses list, is able to instantiate the variables of the dependent clauses list (the defining clauses list).

Of the remaining three clauses, the first two specify the elements of a new model. The new defining clauses list is the existing list to which is appended a further clause indicating that the value of the agent's decision variable set this period will determine the value of his rival's decision variable (as reflected in its market counterpart) after the lag indicated by the agent's belief.

Finally, in the lower pane of the window is the clause to be asserted. All of the variables will have been instantiated by the conditions.

8 Conclusion

In this paper, we have run a round-robin tournament among matched pairs of smart and dumb strategies. The dumb strategies were textbook, linear, Cournot reaction functions and the smart strategies modified the dumb strategies in the light of experience and on the basis of models specified and developed by the smart agents. All of the programming was done in SDML which ensures that the model of the environment and the agents are represented as logical statements and inferences and that all inferences are consistent. Moreover, to avoid nonsense results, the rules used to generate these inferences have been written to avoid redundancy and conflicting outcomes such as multiple levels of outputs. We thus achieve uniqueness as well as consistency. The importance of the uniqueness and consistency of the inferences is that the experiments reported here have a logical basis which has some identifiable degree of rigour. It opens up the possibility of examining in other, more realistic models, the trade-off between rigour and relevance.

Our results indicate that the representation of learning and expectations-formation as a modelling procedure yields strategies which are robustly superior to (at least) strategies represented by linear reaction functions. Obviously, there is much more to be done here. Apart from using finer grids and, so, larger populations of strategies, it will clearly be instructive to use more sophisticated dumb strategies involving random selection of reaction functions, conjectural variations and multiple decision variables.

Nonetheless, we do claim to have demonstrated that scientifically constructed populations of strategies can be assessed for relative strength using a technique which gives greatest weight to success in the most testing situations. The same testing procedure can be applied to different approaches to strategy formation such as the smart and dumb approaches identified here. Moreover, rigour can be maintained to the extent that it is thought to be important in the specification and evaluation of these strategies.

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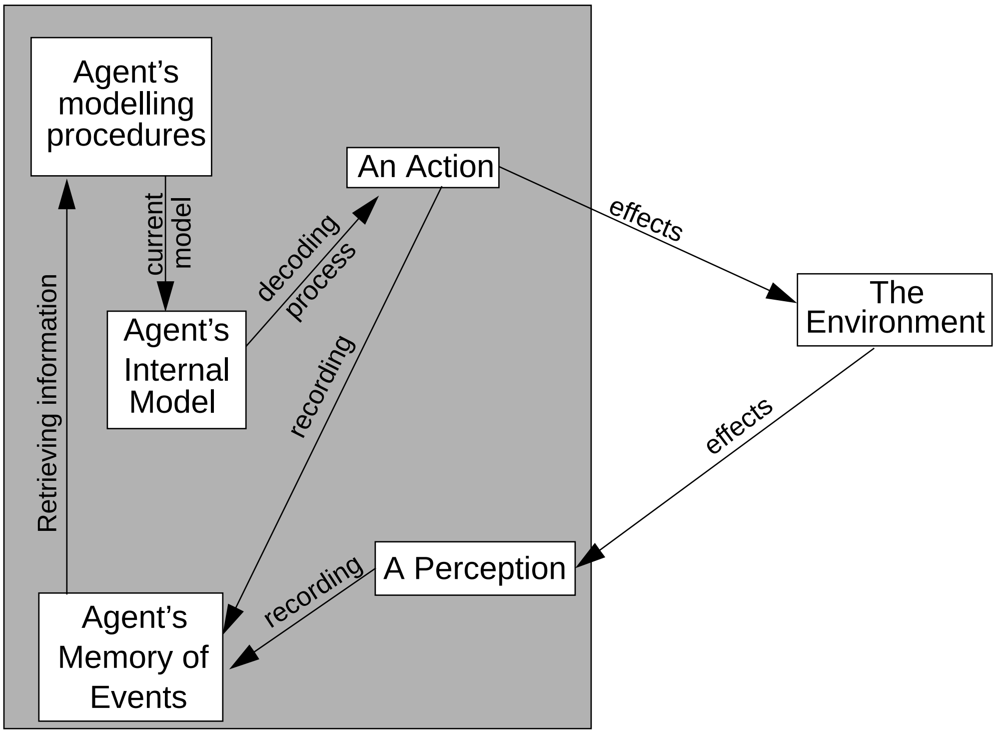

Figure 1: Information flows in learning procedures

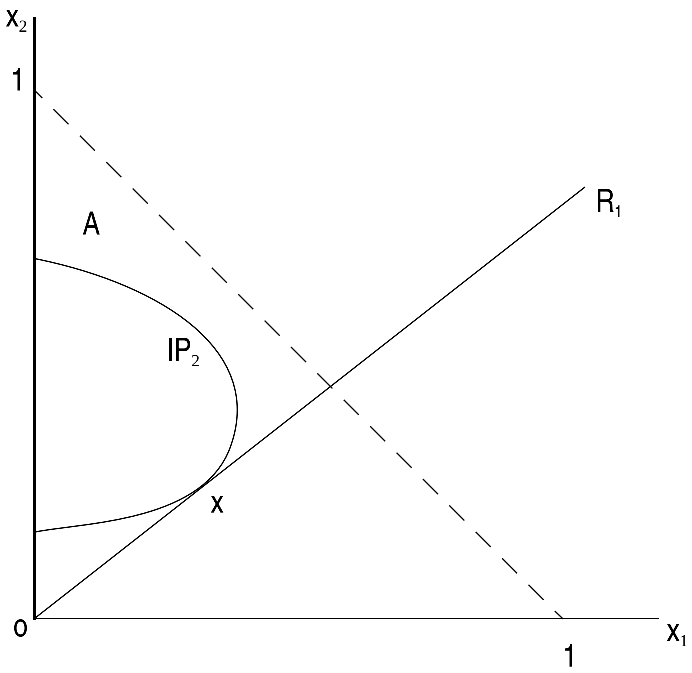

Figure 2: The reaction-function-generating algorithm

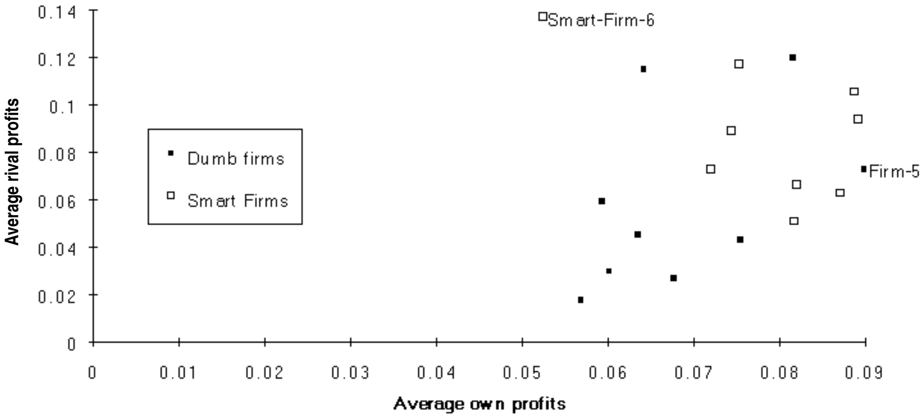

Figure 3: Tournament results — average profits

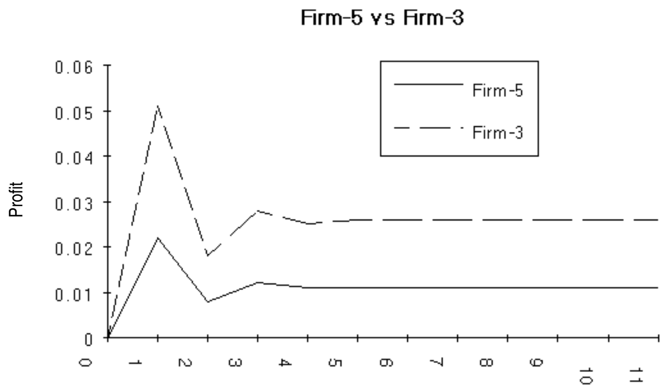

Figure 4: Profit series in game between Firm-5 and Firm-3

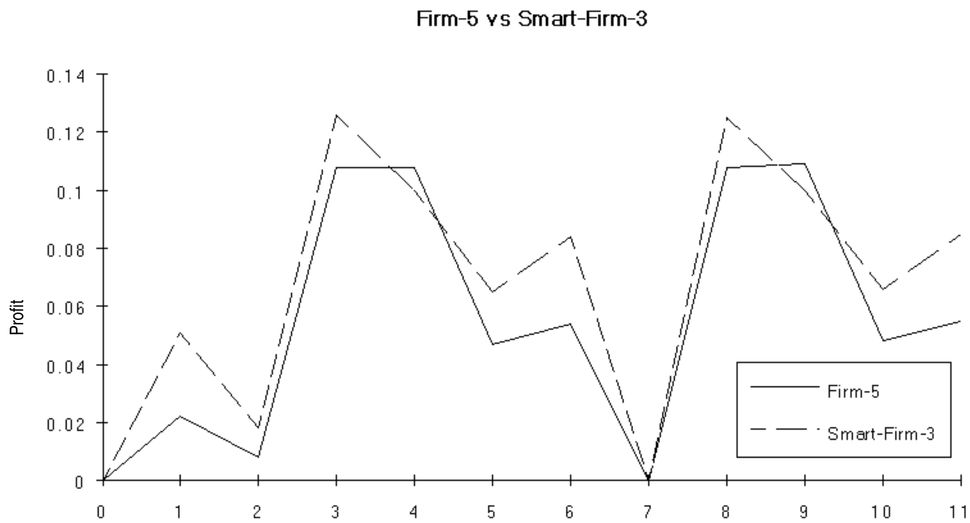

Figure 5: Profit series in game between Firm-5 and Smart-Firm-3

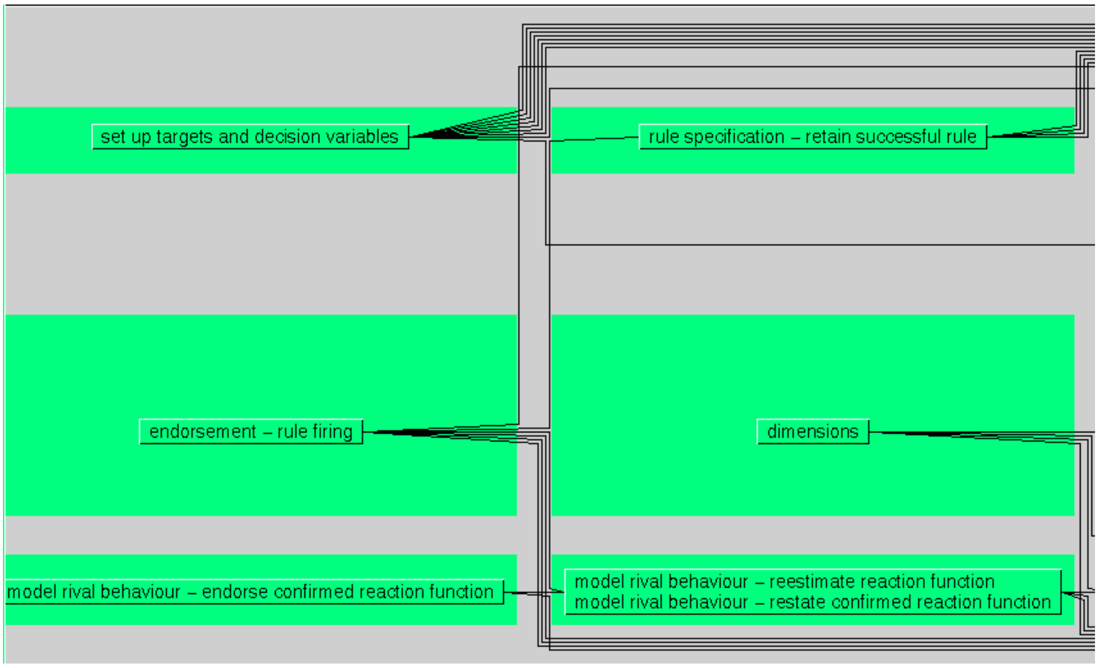

Figure 6(a): Metarulebase dependency network: the start

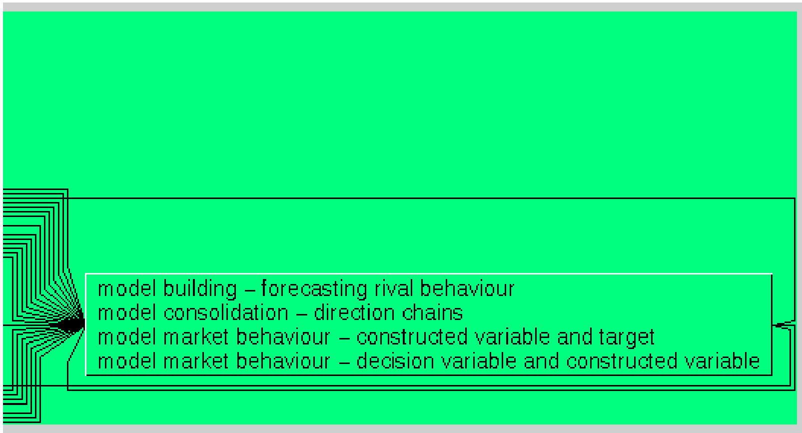

Figure 6(b): Metarulebase dependency network: the finish

```
If a decision variable is known to take the same values as the market value of an own variable and the
market value of a rival variable is believed to be determined with a lag by the own variable, then model
the future rival variable as being determined by the current own decision variable value.
```

```
and
     believed ?beliefID ?rival (compilable ?believedConds) (compilable ?believedActions)\
     isKindOf ?rival firm\
     agentName ?thisFirm\
     not
          = ?thisFirm ?rival\
     productOf ?ownProduct ?thisFirm\
     productOf ?rivalProduct ?rival\
     clauseList ?believedConds and ?believedCondsList\
     includes ?believedCondsList (lag ?t (valueOf ?var ?ownProduct ?ownVarValue))\
     remove (lag ?t (valueOf ?var ?ownProduct ?ownVarValue)) ?believedCondsList
?forwardBelievedCondsList\
     or
          and
               clauseList ?believedActions and ?believedActionsList\
               includes ?believedActionsList (valueOf ?var ?rivalProduct ?rivalVarValue)|
          = ?believedActions (valueOf ?var ?rivalProduct ?rivalVarValue)\
     model ?model1 ?dependentList ?independentList ?defList\
     includes ?dependentList (quantitativeDependentVariable ?var ?ownProduct ?ownVarValue)\
     decisionVariable ?decVar\
     includes ?independentList (quantitativeIndependentVariable ?decVar ?ownProduct
?ownDecVarValue)\
     append ?defList ?forwardBelievedCondsList ?newDefList\
     = ?newDependentList [(quantitativeDependentVariable ?t ?var ?rivalProduct ?rivalVarValue)]\
     generatedName ?newModel model (and
          ?newDependentList\
          ?independentList\
          ?newDefList)
```

```
model ?newModel ?newDependentList ?independentList ?newDefList
```

Figure 7: Metarule entitled *model building - forecasting rival behaviou*

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Firm	Intercept	Slope
Firm-1	0.08	1.55556
Firm-2	0.44	0.555555
Firm-3	0.8	-0.444445
Firm-4	0.8	-0.722222
Firm-5	0.44	-0.222222
Firm-6	0.08	0.277778
Firm-7	0.44	-0.481482
Firm-8	0.8	-0.814815
Firm-9	0.8	-0.861111

Table 1: Generated reaction function parameters

	Avg Own Profit	Avg Rival Profit
Firm-5	0.090	0.073
Smart-Firm-1	0.089	0.094
Smart-Firm-9	0.089	0.105
Smart-Firm-2	0.087	0.062
Smart-Firm-4	0.082	0.066
Smart-Firm-3	0.082	0.051
Firm-7	0.082	0.120
Firm-1	0.075	0.043
Smart-Firm-7	0.075	0.117
Smart-Firm-8	0.074	0.089
Smart-Firm-5	0.072	0.073
Firm-2	0.068	0.027
Firm-6	0.064	0.115
Firm-8	0.063	0.045
Firm-4	0.060	0.030
Firm-9	0.059	0.059
Firm-3	0.057	0.017
Smart-Firm-6	0.052	0.137

Table 2: Average own and rivals' profits in tournament

e =	0.01	0.1	3	5	50
18	SF-2 (0.308)	SF-2 (0.316)	SF-2 (0.481)	SF-3 (0.54)	SF-3 (0.68)
17	SF-3 (0.278)	SF-3 (0.285)	SF-3 (0.473)	SF-2 (0.46)	SF-2 (0.32)
16	SF-4 (0.204)	SF-4 (0.200)	SF-4 (0.045)	SF-1	SF-1
15	SF-1 (0.204)	SF-1 (0.199)	SF-1	SF-4	SF-4
14	F-7 (0.005)	F-5	F-5	F-5	F-5
13	F-5	F-7	SF-9	SF-9	SF-9
12	SF-9	SF-9	F-1	F-1	F-1
11	SF-8	SF-8	F-7	F-7	F-7
10	SF-7	SF-7	SF-7	SF-7	SF-7
9	F-1	F-1	SF-8	SF-8	SF-8
8	SF-5	SF-5	F-9	F-9	F-9
7	F-6	F-6	SF-5	SF-5	SF-5
6	F-2	F-2	SF-6	SF-6	SF-6
5	F-8	F-8	F-6	F-6	F-6
4	F-4	F-9	F-2	F-2	F-2
3	F-9	F-4	F-8	F-8	F-8
2	SF-6	SF-6	F-3	F-3	F-3
1	F-3	F-3	F-4	F-4	F-4

Table 3: Order of extinction or survival strength (% surviving population)
SF-n = Smart-Firm-n; F-n = Firm-n