Web Appendix

Competing under Asymmetric Information: The case of DRAM Manufacturing

Pedro M. Gardete

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1 Appendix

1.1 Description of the DRAM Market

DRAM is a technological variant of what is generically called RAM or 'computer memory'. It is used in a number of electronic appliances like computers, cell phones, printers, game consoles among others. Intel is generally credited for having introduced the first DRAM chip in 1970: the 1103 model featuring 1Kb of storage capacity - 1024 bits - which competed with the dominant technology until then, magnetic cores. Besides Intel, two other American companies started DRAM production in the same year with similar products: Mostek and Advanced Memory Systems (the latter effectively entering the market before Intel, but with a less popular product).[1] DRAM dominated the volatile memory industry in less than a decade. A number of fundamental characteristics of the market were soon apparent and still survive until today. They are discussed below in turn.

1.2 A Race for Memory Density

The production of DRAM chips requires hundreds of procedural steps, and has been described as "one of the most difficult processes of high technology known to man" (Murillo, 1993). This process has only gotten more complex over time, as there have been continued efforts to introduce more memory into the same amount of physical space.

Memory chips are etched on a silicon disc called wafer. Given that the cost of a wafer is basically constant across production technologies, it follows that fitting double as many memory units into the same wafer results in halving the variable production costs. In fact, memory density is the fundamental cost determinant for the DRAM production

[1] See Murillo (1993) for a description of the DRAM industry from 1970 until 1993.

process. Production decisions depend strongly on it, over and above other cost factors such as wages or the prices of silicon and of other raw materials.

1.3 International Competition

Except for its earlier stages, competition in the DRAM industry has taken place at the international scale. The introduction of the 1103 chip in 1970 had already caused the appearance of clones by other 19 companies as of 1972, including the first Japanese rival, NEC. By 1976 two Japanese companies had subsidiaries in the U.S.A., and one of them (NEC) received its first big order of DRAM chips from Honeywell ($5 million worth). This was the fruit of continued efforts by the Japanese companies to address reliability and provide fast access performance in their chips. Soon, the so-called 'four sisters' (NEC, Toshiba, Fujitsu and Hitachi) had managed to effectively enter the American market.[2]

In October 1985 Intel announced it was leaving the DRAM production altogether in order to focus on the microprocessor. In the same year Motorola declared it too was abandoning the market.[3] A period of Japanese dominance initiated, but it was short-lived: in September 1986, a U.S.A.-Japan Semiconductor Agreement forced Japanese firms to stop "dumping" across world markets, and established "fair market values" for their products. The agreement was aimed at benefiting American and European producers through raising Japanese product prices. Instead, it changed the competitive landscape in an unpredicted fashion: it opened the door for Korean firms who had been acquiring technology licenses and had started to participate in the capital of American companies (e.g.: Samsung purchased 2.7% capital of the American DRAM manufacturer Micron in the mid-80's). Concurrently, the quality-orientation that had served Japanese firms well in the past may have played a role in their demise: The shift in use of DRAM from mainframes to personal computers privileged low costs rather than quality and reliability.[4] Korean firms eventually surpassed both Japanese and North American ones in production quantities.

1.4 A Commodity with Turbulent Prices Descents

Price descents have been part of the DRAM market since its inception. For instance, the price of the 1103 chip came down from $60 in 1970 to only $4 three years later. The downward trend in prices per bit has remained until today. The reference spot price for a kilobit of DRAM was of 0.0003 cents of a dollar as of April 2010,[5] a reduction of 7 orders of magnitude in price per memory unit with respect to the original level of 1970. The improvements in production technologies are the main factor responsible for long-term decreases in market prices. Similar to what happens in other semiconductor industries, the price per unit decline is a result of firm coordination around Moore's law. In the DRAM industry this law has been translated to state that the number of bits per wafer

[2]A number of enabling factors are documented: availability of qualified human resources, low cost of capital, "deep pockets" linked to the Keiretsu firm structure, among others. In 1980 the differences in product reliability were measured repeatedly, giving significant advantage to the Japanese producers.

[3]Both firms reentered the market in 1987 as resellers.

[4]As an example, today's DRAM modules used in computer servers often have error checking and error-correcting mechanisms (e.g.: parity bits), which are absent in most of personal computers due to cost reasons.

[5]As noted on http://www.dramexchange.com on April 13th, 2010.

doubles every two years.[6] This translates into lower marginal production costs over time, which enables firms to increase capacity and production levels profitably. Although at a given moment in time different firms have different technological capabilities, Moore's law acts as a focal point firms coordinate around of in terms of the expected rate of technological innovation, much in the spirit of Schelling (1960). During the sample only one alliance is able disrupt the innovation rate, but only momentarily. A memory density advantage reduces marginal production cost and therefore creates incentive for higher capacity investments and higher production levels.

Another empirical regularity is that the price descent path is not smooth because economic conditions impact the performance of the DRAM industry, pushing prices up and down around the descent path over time.

Finally, although not all DRAM is created equal, at a given moment in time most differences are introduced at the final packaging level. It is usually considered as a commodity and is mostly traded through spot contracts.[7]

2 Model Details

2.1 Conditional Distributions

The relation

$$log(s_{it}) = log(\varepsilon_t) + log(\eta_{it}). \tag{1}$$

is used to determine the posterior distributions of one demand signal given the remaining ones. The posterior distribution of the competitors' demand signals given firm 1's demand signal (without loss of generality) becomes:

$$\begin{array}{c} s_{2t} \\ \vdots \\ s_{Nt} \end{array} \Bigg|_{s_{1t} \sim LogN} \left(\begin{bmatrix} \frac{\sigma_\varepsilon^2}{\sigma_\varepsilon^2+\sigma_\eta^2} log\left(s_{1t}\right) \\ \vdots \\ \frac{\sigma_\varepsilon^2}{\sigma_\varepsilon^2+\sigma_\eta^2} log(s_{1t}) \end{bmatrix}, \begin{bmatrix} \sigma_\eta^2 + \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} & \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} & \cdots & \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} \\ \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} & \sigma_\eta^2 + \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} & \cdots & \frac{\sigma_u^2\sigma_\eta^2}{\sigma_u^2+\sigma_\eta^2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} & \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} & \cdots & \sigma_\eta^2 + \frac{\sigma_\varepsilon^2\sigma_\eta^2}{\sigma_\varepsilon^2+\sigma_\eta^2} \end{bmatrix} \right) \tag{2}$$

which suggests that a firm's own demand signal is informative about the demand signals of others.

2.2 Quantity Competition facing a Constant Elastic Demand Curve

Firms face a Cournot competition setting under symmetric information, where quantities are bounded above by capacity levels. For simplicity, consider the static problem that

[6] See http://www.intel.com/pressroom/kits/events/moores_law_40th/.

[7] In line with the commodity product view, see http://www.dramexchange.com for an example of a DRAM price index.

firm i solves:

$$\begin{array}{ll} \underset{q_i}{max} & E_{\varepsilon}\left[\mu\left(\sum_j q_j\right)^{\beta}\varepsilon - c_i \middle| s\right] q_i \\ s.t. & q_i \leq K_i \end{array} \tag{3}$$

where s is a vector of demand signals related to the unobservable demand shock ε.

It is possible to get an algebraic solution to the firms' static profit maximization problem and hence speed up moment computation. First, start with the case of unconstrained production (no capacity constraints):

$$\underset{q_i}{max} \quad E_{\varepsilon}\left[\mu\left(\sum_j q_j\right)^{\beta}\varepsilon - c_i \middle| s\right] q_i \tag{4}$$

$$= \tag{5}$$

$$\underset{q_i}{max} \quad \left(\mu\left(\sum_j q_j\right)^{\beta} E_{\varepsilon}\left[\varepsilon | s\right] - c_i\right) q_i \tag{6}$$

The first-order condition of (4) for firm i becomes:

$$\mu E_{\varepsilon}\left[\varepsilon | s\right] Q^{\beta-1}\left(Q + \beta q_i\right) = c_i,\ Q \equiv \sum_j q_j \tag{7}$$

Summing the FOC's of all firms, one gets:

$$\begin{aligned} \mu E_{\varepsilon}\left[\varepsilon | s\right] Q^{\beta}\left(n+\beta\right) &= \sum_{j\in n} c_j \\ \Leftrightarrow Q &= \left(\frac{\sum_{j\in n} c_j}{\mu E_{\varepsilon}\left[\varepsilon | s\right]\left(n+\beta\right)}\right)^{1/\beta} \end{aligned} \tag{8}$$

Finally, (7) and (8) imply:

$$q_i^* = \frac{1}{\beta}\frac{\left(n+\beta\right)c_i - \sum_{j\in n} c_j}{\sum_{j\in n} c_j}\left(\frac{\sum_{j\in n} c_j}{\mu E_{\varepsilon}\left[\varepsilon | s\right]\left(n+\beta\right)}\right)^{1/\beta}.$$

Solving the Kuhn-Tucker conditions implies searching over all possible cases. One strategy to solve them is to guess which are the binding constraints first, solve the appropriate system of equations and finally check that the remaining Kuhn-Tucker conditions are satisfied. When some capacities bind, the shadow costs λ_i are solved for numerically while the interior solutions can still be calculated via a closed form. For example, consider the two firm case where the current guess is that firm 2's capacity constraint is binding, but not firm 1's. Then, it is necessary (but not sufficient) that the solution satisfies

$$\begin{aligned} \mu E_{\varepsilon}\left[\varepsilon | s\right] Q^{\beta-1}\left(Q + \beta q_1\right) &= c_1 \\ \mu E_{\varepsilon}\left[\varepsilon | s\right] Q^{\beta-1}\left(Q + \beta q_2\right) &= c_2 + \lambda_2 \end{aligned} \tag{9}$$

One can combine the marginal production cost and the shadow cost of capacity of firm 2: $c_2^{'} \equiv c_2 + \lambda_2$. Then, q_1^* is given by

$$q_1^* = \frac{1}{\beta}\frac{\left(2+\beta\right)c_1 - \left(c_1 + c_2^{'}\right)}{c_1 + c_2^{'}}\left(\frac{c_1 + c_2^{'}}{\mu E_{\varepsilon}\left[\varepsilon | s\right]\left(2+\beta\right)}\right)^{1/\beta}.$$

Only the shadow price of capacity of firm 2 is required to be solved numerically using the single equation (9). Indeed, one needs to solve as many equations as the number of predicted corners in the solution.

2.3 Effect of σ_η^2 on Operating Profits when Capacity is Large

By the expressions above a firm's expected profit is equal to

$$\kappa \int_{-\infty}^{+\infty} \exp\left\{ \frac{\sigma_\varepsilon^2 \left(\sigma_\eta^2 - 2\sum_{i\in n} \log\left(s_{it+1}\right)\right)}{2\beta\left(4\sigma_\varepsilon^2 + \sigma_\eta^2\right)} \right\} dF_{\sum_{i\in n} log(s_{it+1})} \tag{10}$$

where

$$\kappa \equiv -\frac{\left(\sum_{i\in n} c_i\right)^{\frac{1}{\beta}-1} \left(\sum_{i\in n} c_i - c_i\left(n+\beta\right)\right)^2}{\mu^{\frac{1}{\beta}} \beta \left(n+\beta\right)^{\frac{1+\beta}{\beta}}}$$

is positive due to the sign of β. By noting that $\sum_{i\in n} log\left(s_{it+1}\right) \sim N\left(0, 4\left(4\sigma_\varepsilon^2 + \sigma_\eta^2\right)\right)$ it is easy to calculate the integral in expression (10), which yields

$$\frac{\partial \pi_{it+1}^*\left(K_{t+1}, \sigma_\eta^2\right)}{\partial \sigma_\eta^2} = -\kappa \exp\left\{ \frac{\sigma_\varepsilon^2\left(\beta\sigma_\eta^2 - 4\sigma_\varepsilon^2\right)}{2\beta^2\left(4\sigma_\varepsilon^2 + \sigma_\eta^2\right)} \right\} \frac{2\left(1+\beta\right)\sigma_\varepsilon^2}{\beta^2\left(4\sigma_\varepsilon^2 + \sigma_\eta^2\right)} \leq 0$$

since $\beta > -1$ and $\kappa > 0$.

3 Moore's Law and Demand Expansion

We now perform a simple analysis that suggests that the assumptions and model fit the positive production trend well. To simplify the analysis consider the case of firms competing in a simple Cournot oligopoly setting while facing a constant elastic demand curve. In this case the total output in the market at time t is given by

$$Q_t^* = \left(\frac{\sum_{j\in n} c_{jt}}{\mu\left(n+\beta\right)}\right)^{1/\beta} \tag{11}$$

where n is the number of firms, $\sum_{j\in n} c_{jt}$ is the sum of the firms' marginal costs, and parameters β, μ characterize the demand function.[8] Consider now the ratio of subsequent market production levels, as implied by equation (11):

$$\begin{aligned} \frac{Q_{t+1}}{Q_t} &= \left(\frac{\sum_{j\in n} c_{jt+1}}{\sum_{j\in n} c_{jt}}\right)^{1/\beta} \\ \Leftrightarrow \quad \left(\frac{Q_{t+1}}{Q_t}\right)^\beta &= \frac{\sum_{j\in n} c_{jt+1}}{\sum_{j\in n} c_{jt}} \end{aligned} \tag{12}$$

[8] We use the inverse demand function $P_t = \mu Q_t^\beta$ in this example. The result also holds if agents compete under (imperfect) common information.

The equality above reveals that the ratio of subsequent production levels moderated by the inverse elasticity of demand (β) should be equal to the ratio of subsequent (total) production costs. We inform the left hand side of equation (12) by using the production data and the estimated parameter β from the demand function, and use Moore's law to predict its right hand side. Balancing equation (12) suggests that Moore's law effect on production costs is enough to explain the trend in the observed market production. However, if for example the left hand side is significantly higher than the right hand side we have reason to believe that Moore's law alone cannot drive the trend in production quantities, and that other factors such as market expansion over time are required to rationalize the output growth in the data.

Moore's law predicts that costs should halve every two years, and in our model one period is equal to one quarter. One can calculate the quarterly rate of implied cost decrease by solving equation $\sum_{j\in n} c_{jt}\left(1+r_{Moore}\right)^{8} = \frac{\sum_{j\in n} c_{jt}}{2}$ w.r.t. r_{Moore}. This is approximately equal to -0.083. It follows that Moore's law prediction of ratio $\frac{\sum_{j\in n} c_{jt+1}}{\sum_{j\in n} c_{jt}}$ (the right hand side of equation (12)) is equal to $1-0.083=0.917$. Consider now the prediction of the demand curve together with the production levels in the dataset. Using the production data and the estimated parameter β we calculate the left hand side of expression (12) to be equal to $1.116^{-0.938}=0.901$. This figure is close to the prediction implied by Moore's law. The fact that we find that production costs should decrease to 91.7% of their base level each period according to Moore's law and that the production data in conjunction with the recovered demand elasticity predict a quarterly cost decrease to 90.1% of the base value in each period provides some confidence that the reductions in costs drive the increase in quantities over time. We find that no direct market expansion effects are necessary to explain the positive trend in production levels, but rather that gains in efficiency (and the resulting low prices) provide sufficient explanation.

4 Model Fit

Table 1 compares the actual and predicted moments to illustrate the model fit.

Table 1: Model Fit Evidence from Matched Moments

Statistical Moments	Actual Data	Std. Deviation (Data)	Model Prediction
$E_t\left[Q_t\right]$	209.0	135.0	213.2
$E_t\left[Q_t^2\right]$	61,917.4	67,113.7	59,745.8
$E_{i,t}\left[K_{it}\right]$	54.7	35.5	58.3
$E_{i,t}\left[K_{it}^2\right]$	4,545.5	4,771.1	4,358.9
$E_{i,t}\left[K_{it}.K_{jt}\right]$	3,974.5	4,663.9	3,919.8
$E_{i,t}\left[K_{it+1}-K_{it}\right]$	5.0	3.8	4.9

References

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Schelling, T. C. (1960): *The strategy of conflict*. London: Oxford University Press.