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The Role of Information Structure in Dynamic Games of Knowledge Accumulation

by

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Abstract

This paper analyzes the influence of information structure on the process of knowledge accumulation in a differential game of duopolistic R&D competition. By comparing open-loop and feedback Nash equilibria, representing imperfect and perfect information structures, we show that in the feedback equilibrium the stationary levels of knowledge are larger than in the corresponding open-loop equilibrium. Information about the rival's stock of technological knowledge creates a strategic incentive to raise own knowledge in order to preempt the rival's R&D activity. As a consequence, each firm seeks for more knowledge than it would if it could not influence its rival's accumulation. Therefore, information structure is an important determinant of firms' innovative behavior.

Zusammenfassung

Dieser Beitrag präsentiert ein Differentialspiel des duopolistischen F&E-Wettbewerbs, um den Einfluß der Informationsstruktur auf den Prozeß der Wissensakkumulation zu analysieren. Aus einem Vergleich der open-loop und feedback-Gleichgewichte, denen unvollkommene bzw. vollkommene Informationsstrukturen zugrundeliegen, geht hervor, daß die stationären Niveaus des technologischen Wissens im feedback-Gleichgewicht größer sind als im open-loop-Gleichgewicht. Informationen über den Stand der Technologie des Konkurrenten schaffen einen strategischen Anreiz, das eigene Wissen zu erhöhen, um dadurch die F&E-Aktivitäten des Konkurrenten zu bremsen. So strebt jedes Unternehmen ein höheres Maß an technologischem Wissen an, als es dies ohne Einflußmöglichkeiten auf den Akkumulationsprozeß des Konkurrenten tun würde. Der Informationsstruktur kommt damit die Rolle eines wichtigen Einflußfaktors auf die private Innovationstätigkeit zu.

2. Imperfect Information: The Open-Loop Nash Equilibrium

If we assume that firms have no information about the rival's current stock of knowledge, we have to solve the model in terms of an open-loop Nash equilibrium. According to this concept firms do not react to the rival's R&D activities. Obviously, without information about rival activities they cannot react. As a consequence, j's R&D activity cannot be influenced by i's knowledge accumulation during the game.

Defining $V^i = e^{rt}J^i$, the open-loop Hamilton-Jacobi-Bellman equations of the system (1) to (4) are

$$(5) \qquad rV^i = \max_{x_i(t)} \left\{ (s - w_i - w_j)\, w_i - x_i + V^i_{w_i} (2x_i)^{0.5} \right\}, \quad i=1,2\,, \quad i \neq j$$

with the current value Hamiltonian

$$(6) \qquad H^i = (s - w_i - w_j)\, w_i - x_i + V^i_{w_i} (2x_i)^{0.5}$$

where $V^i_{w_i}$ is the costate variable for firm i. According to the maximum principle, the optimal R&D path must satisfy the necessary first-order conditions

$$(7) \qquad H^i_{x_i} = -1 + V^i_{w_i} (2x_i)^{-0.5} = 0$$

and

$$(8) \qquad H^i_{w_i} = s - 2\,w_i - w_j = rV^i_{w_i} - \dot{V}^i_{w_i}\,.$$

Nonnegativity constraints on R&D activities are not tight, the transversalitiy conditions will be satisfied, and the second order conditions are fullfilled since the Hamiltonian is concave in x and w. Due to the special form of h(x) in (4), we derive from (7) $V^i_{w_i} = \dot{w}_i$ and, hence, $\dot{V}^i_{w_i} = \ddot{w}_i$. Substituting these expressions for $V^i_{w_i}$ and $\dot{V}^i_{w_i}$ in (8) yields the linear second-order differential equation

$$(9) \qquad \ddot{w}_i - r\,\dot{w}_i - 2\,w_i - w_j + s = 0\,.$$

The steady-state value of w_i is characterized by $\ddot{w}_i = \dot{w}_i = 0$, $i = 1,2$. From (9) we derive symmetric stationary levels for both firms' technological knowledge

$$(10) \qquad w^* = s / 3\,,$$

which yield stationary profit streams

(11) $\pi^* = s^2 / 9$.

The stationary stocks of knowledge and the profits are increasing with market size s but are independent of the interest rate r. To derive the open-loop Nash equilibrium R&D strategies that yield the adjustment trajectories, we define $\dot{w}_i = z_i$, implying $\ddot{w}_i = \dot{z}_i = rz_i + 2\, w_i + w_j$, to solve the homogeneous part of equation (9) with $s=0$ by using the four equation system

$$(12)\quad \begin{bmatrix} \dot{w}_i \\ \dot{z}_i \\ \dot{w}_j \\ \dot{z}_j \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & r & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 2 & r \end{bmatrix} \begin{bmatrix} w_i \\ z_i \\ w_j \\ z_j \end{bmatrix} .$$

The characteristic equation

$$(13)\quad [(r - \lambda)\lambda]^2 + 4(r - \lambda)\lambda + 3 = 0$$

yields four eigen values, two of which are negative

$$(14a)\quad \lambda_1 = (r - \sqrt{r^2 + 12}\,)/2 ,$$

$$(14b)\quad \lambda_2 = (r - \sqrt{r^2 + 4}\,)/2 ,$$

and the other two of which are positive

$$(14c)\quad \lambda_3 = (r + \sqrt{r^2 + 12}\,)/2$$

$$(14d)\quad \lambda_4 = (r + \sqrt{r^2 + 4}\,)/2 .$$

Therefore, there exists a unique pair of open-loop Nash equilibrium R&D strategies. Using the initial values w_{i0} and w_{j0} as well as the stationary value w^*, they are described by the trajectories of technological knowledge

$$(15)\quad w_i = [\, (w_{i0} + w_{j0})/2 - w^* \,]\, e^{\lambda_1 t} + [\, (w_{i0} - w_{j0})/2 \,]\, e^{\lambda_2 t} + w^*$$

and by the corresponding trajectories of R&D investment

$$(16)\quad x_i = \left\{ [\, (w_{i0} + w_{j0})/2 - w^* \,]\, \lambda_1 e^{\lambda_1 t} + [\, (w_{i0} - w_{j0})/2 \,]\, \lambda_2 e^{\lambda_2 t} \right\}^2 / 2 .$$

4. Perfect Information: The Feedback Nash Equilibrium

In this section the information structure for the game is altered to allow firms to make their R&D decisions as functions of both firms' current stocks of knowledge. Under such circumstances a firm need not commit itself to an R&D time path in advance but rather is permitted to make R&D choices that are contingent upon how the stocks of knowledge evolve. The following Hamilton-Jacobi-Bellman equations provide a set of necessary conditions for the feedback R&D strategies.

$$(17)\quad rV^i = \max_{x_i(t)} \left\{ (s - w_i - w_j)\, w_i - x_i + V^i_{w_i}\,(2x_i)^{0.5} + V^i_{w_j}\,(2x_j^*)^{0.5} \right\}, \quad i=1,2, \quad i \neq j$$

with the current value Hamiltonian

$$(18)\quad H^i = (s - w_i - w_j)\, w_i - x_i + V^i_{w_i}\,(2x_i)^{0.5} + V^i_{w_j}\,(2x_j^*)^{0.5}.$$

The first order conditions for the maximization with respect to the controls are the same as in the open-loop case

$$(19)\quad H^i_{x_i} = -1 + V^i_{w_i}\,(2x_i)^{-0.5} = 0.$$

Substituting for optimal R&D activities of both firms i = 1,2 from (19) into (17) yields

$$(20)\quad rV^i = (s - w_i - w_j)\, w_i + (V^i_{w_i})^2/2 + V^i_{w_j} V^j_{w_j}.$$

As suggested by Reynolds (1987) we propose a quadratic solution function

$$(21)\quad V^i = \alpha + \beta\, w_i + \gamma\, w_j + \delta\, w_i^2/2 + \varepsilon\, w_i w_j + \xi\, w_j^2/2$$

where α, β, γ, δ, ε, and ξ are six yet undetermined parameters which have to be expressed in terms of the exogenous parameters r and s in order to find an explicit solution function. Differentiation of (21) with respect to the state variables gives

$$(22)\quad V^i_{w_i} = \dot{w}_i = \beta + \delta\, w_i + \varepsilon\, w_j$$

and

$$(23)\quad V^i_{w_j} = \gamma + \varepsilon\, w_i + \xi\, w_j.$$

Substituting (21), (22), and (23) back into (20) yields the following restrictions for the constant term and the terms w_i, w_j, w_i^2, $w_i w_j$, and w_j^2 which have all to be fullfilled in order for (21) to be valid for all states of the system:

(24a) $-r\alpha + \beta^2/2 + \beta\gamma = 0$,

(24b) $-r\beta + s + \beta\delta + \beta\varepsilon + \gamma\varepsilon = 0$,

(24c) $-r\gamma + \beta\varepsilon + \gamma\delta + \beta\xi = 0$,

(24d) $-r\delta/2 - 1 + \delta^2/2 + \varepsilon^2 = 0$,

(24e) $-r\varepsilon - 1 + 2\delta\varepsilon + \varepsilon\xi = 0$,

(24f) $-r\xi/2 + \varepsilon^2/2 + \delta\xi = 0$.

The non-linear equation system (24a) to (24f) has the same structure as the more general system discussed by Reynolds (1987, 83). From (24d) we can solve for

(25) $\delta = r/2 \pm \sqrt{r^2/4 + 2 - 2\varepsilon^2}$.

From (24f) we derive

(26) $\xi = \varepsilon^2/(r - 2\delta)$.

Substituting for ξ in (24e) yields

(27) $\varepsilon^3 - r^2\varepsilon - r = 4\varepsilon\delta^2 - (4r\varepsilon + 2)\delta$.

Substituting δ from (25) into (27), rearranging terms and squaring yields

(28) $81\,\mu^3 - 18\,m\,\mu^2 + (m^2 + 8)\,\mu - m = 0$,

where $\mu \equiv \varepsilon^2$ and $m \equiv r^2 + 8$. The cubic equation (28) can be solved along the lines suggested by Bronstein, Semendjajew (1991, pp. 131). Its discriminant can be calculated as

(29) $D = (-m^4 + 26.75\,m^2 + 512)\,3^{-15}$.

Since m>8, the discriminant is negative. Thus, equation (28) has three real and distinct roots

(30a) $$\mu_1 = 2\left\{ m - \sqrt{m^2 - 24}\,\cos(\theta/3) \right\} / 27$$

(30b) $$\mu_2 = 2\left\{ m - \sqrt{m^2 - 24}\,\cos((\theta+2\pi)/3) \right\} / 27$$

(30c) $$\mu_3 = 2\left\{ m - \sqrt{m^2 - 24}\,\cos((\theta+4\pi)/3) \right\} / 27$$

where θ is defined by: $\tan\theta = -\sqrt{-D}/R$ with D from (29) and $R = (m^3 - 44.5\,m)\,3^{-9}$. For m=8 we calculate $\theta \approx -1.094$. For m>8, θ is negative and strictly increasing in m. Therefore, $\cos(\theta/3)$ is a positive, increasing function of m, $\cos((\theta+2\pi)/3)$ is a negative, decreasing function of m and $\cos((\theta+4\pi)/3)$ is a negative, increasing function of m. Given these characteristics, it is straightforward to show that $0 < \mu_{1,2,3} < m/8$. Thus, there exist six real and distinct roots for ε

(31a) $$\varepsilon_{1,2} = \pm\sqrt{2\left\{ m - \sqrt{m^2 - 24}\,\cos(\theta/3) \right\} / 27}$$

(31b) $$\varepsilon_{3,4} = \pm\sqrt{2\left\{ m - \sqrt{m^2 - 24}\,\cos((\theta+2\pi)/3) \right\} / 27}$$

(31c) $$\varepsilon_{5,6} = \pm\sqrt{2\left\{ m - \sqrt{m^2 - 24}\,\cos((\theta+4\pi)/3) \right\} / 27}$$

Inserting in (25) yields six real and distinct roots for δ.

(32) $$\delta_{1,2,3,4,5,6} = r/2 \pm \sqrt{m/4 - 2\mu_{1,2,3}}\ .$$

As we will show, the only stable solution of the candidate pairs of ε and δ is given by

(33) $$\varepsilon^* = -\sqrt{2\left\{ m - \sqrt{m^2 - 24}\,\cos(\theta/3) \right\} / 27}$$

and

(34) $$\delta^* = r/2 - \sqrt{m/4 - 2\varepsilon^{*2}}\ .$$

Due to the characteristics of cosine functions, it can be established that $0 < \varepsilon^{*2} < m/36$ for all m > 8. In addition, an interest rate r < 0.5 is sufficient (but not necessary) for the relation

(35) $\delta^* < \varepsilon^* < 0$.

Solving for γ in (24b) and inserting the resulting expression together with ξ from (26) in (24c) gives the optimal value of β in terms of ε^* and δ^*.

(36) $\beta^* = - s\,(\delta^* - r)\,/\,[\,(\delta^* + \varepsilon^* - r)(\delta^* - r) - \varepsilon^{*2}(1 + \varepsilon^*/(r - 2\delta^*))\,]$

Finally, α can be calculated from (24a). Having solved for all parameters in (21), we can conclude that (21) is a valid solution function.

Therefore, it can be seen from (22) and (35) that in the feedback model each firm's pace of knowledge accumulation is a decreasing function of its own current stock of knowledge and of its rival's current stock of knowledge. The latter result describes a strategic preemption effect of R&D activity due to perfect information of the competitors. Technological advance of one firm unambiguously reduces the rival's R&D efforts. The consequences of this preemption effect will be seen when we have readily solved the model.

Let us now turn back to the first-order conditions of our dynamic optimization problem. Since we conclude from (19) and (22) that $\dot{w}_j = \beta + \delta^* w_j + \varepsilon^* w_i$, $j = 1,2$, $i \neq j$, the optimal R&D strategy must satisfy in addition to (19) the two further first order conditions

(37) $H^i_{w_i} = s - 2\,w_i - w_j + \varepsilon^*\,V^i_{w_j} = rV^i_{w_i} - \dot{V}^i_{w_i}$.

and

(38) $H^i_{w_j} = - w_i + \delta^*\,V^i_{w_j} = rV^i_{w_j} - \dot{V}^i_{w_j}$.

Using the expressions $V^i_{w_i} = \dot{w}_i$ and $\dot{V}^i_{w_i} = \ddot{w}_i$ in (37) yields

(39) $V^i_{w_j} = (\,- s + 2\,w_i + r\,\dot{w}_i - \ddot{w}_i + w_j\,)\,/\,\varepsilon^*$.

Differentiating with respect to time and again using (22) yields

(40) $\dot{V}^i_{w_j} = (\,\beta + \varepsilon\,w_i + 2\,\dot{w}_i + r\,\ddot{w}_i - \dddot{w}_i + \delta\,w_j\,)\,/\,\varepsilon$.

Substituting (39) and (40) in (38) yields the linear third-order differential equation

(41) $\dddot{w}_i = (2r - \delta^*)\,\ddot{w}_i + (2 - r(r - \delta^*)\,\dot{w}_i - 2\,(r - \delta^*)\,w_i - (r - 2\delta^*)\,w_j + s\,(r - \delta^*) + \beta^*$.

The stationary values for w_i and w_j are characterized by $\dddot{w}_i = \ddot{w}_i = \dot{w}_i = 0$, i=1,2. Inserting in (22) and (41) we calculate the steady-state levels for the knowledge of both firms

$$(42) \quad w^* = s \, / \, [\, 3 + (\varepsilon^*/(r - \delta^*))\,]$$

which yield stationary profit streams

$$(43) \quad \pi^* = [\, 1 + (\varepsilon^*/(r - \delta^*))\,]\, s^2 \, / \, [\, 3 + (\varepsilon^*/(r - \delta^*))\,]^2 \, .$$

The stationary know-how levels (10) and (42) differ by the negative term $-1 < \varepsilon^*/(r - \delta^*) < 0$ in the denominator of (42). This means that in the steady-state the feedback solution for knowledge per firm exceeds the open-loop steady state solution for knowledge. The reason is that in the feedback equilibrium each firm recognizes that its current R&D activities will preempt some amount of later R&D investments by its rival. Recognition of this strategic aspect of current R&D activities leads each firm to overinvest in R&D relative to the non-strategic behavior in the open-loop case. Concurrently, as can be seen by relating (11) to (43), stationary profit levels reduce due to the overinvesting strategies of the rivals. Thus innovative behavior and profit performance depend decisively on whether firms have perfect information about the rival's situation or not.

It remains to show that there exist stable adjustment trajectories to the steady-states in order for the transversality condition to be satisfied. We define $\dot{w}_i = z_i$ and $\ddot{w}_i = y_i$ to solve the homogeneous part of equation (41) by using the four equation system

$$(44) \quad \begin{bmatrix} \dot{y}_i \\ \dot{z}_i \\ \dot{w}_i \\ \dot{w}_j \end{bmatrix} = \begin{bmatrix} 2r-\delta^* & 2-r(r-\delta^*) & -2(r-\delta^*) & -(r+2\delta^*) \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \varepsilon & \delta \end{bmatrix} \begin{bmatrix} y_i \\ z_i \\ w_i \\ w_j \end{bmatrix}$$

The characteristic equation is

$$(45) \quad \lambda^4 - 2r\,\lambda^3 - (\delta^{*2} - r\delta^* - r^2 + 2)\,\lambda^2 + (r\delta^{*2} - r^2\delta^* + 2r)\,\lambda - 2\,(r - \delta^*) + (r - 2\delta^*)\,\varepsilon = 0 \, .$$

As can be shown there are two real and distinct negative roots $-\infty < \lambda_1 < \delta^*$ and $\delta^* < \lambda_2 < 0$ as well as two roots with positive real parts. . Thus, there exists a unique pair of feedback Nash equilibrium R&D strategies that are described by the trajectories of knowledge

$$(46) \quad w_i = [\, (w_{it_0} + w_{jt_0})/2 - w^* \,]\, e^{\lambda_1 t} + [\, (w_{it_0} - w_{jt_0})/2 \,]\, e^{\lambda_2 t} + w^*$$

and by the corresponding trajectories of R&D investment

$$(48)\quad x_i = \left\{ \left[(w_{it_0} + w_{jt_0})/2 - w^* \right] \lambda_1 e^{\lambda_1 t} + \left[(w_{it_0} - w_{jt_0})/2 \right] \lambda_2 e^{\lambda_2 t} \right\}^2 / 2,$$

where the vector $(w_{it_0}, w_{jt_0})'$ denotes any possible states of the game and not only the initial state (w_{i0}, w_{j0}). Finally, each parameter pair $(\varepsilon,\delta) \neq (\varepsilon^*,\delta^*)$ can be shown to yield unstable trajectories and does not constitute a feedback equilibrium.

5. Summary and Concluding Remarks

The paper presented a game theoretic analysis of duopolistic rivalry in R&D. Using an explicitly specified model we showed that information structure has an important impact on the innovation process and the stationary levels of technological knowledge. The results indicate that knowledge accumulation can be used preemptively. In the open-loop Nash equilibrium firms' R&D activities are independent of the unknown rival's current stock of knowledge. However, in the feedback Nash equilibrium, relevant under a perfect information structure, the firms' R&D activities are decreasing functions of the rival's current stock of knowledge. Compared with the open-loop model, this creates a symmetric incentive for both firms to raise knowledge in order to preempt the rival's R&D investment. This preemption effect is responsible for the result that stationary levels of technological knowledge for the feedback Nash equilibrium exceed stationary levels for the open-loop Nash equilibrium. Of course, generalizing these results to less restrictive specifications would be important. But it is very difficult to obtain closed-form solutions for differential games. At present it only remains to hope that the findings will hold under more general circumstances, too.

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