

# Silver Signals: Twenty-Five Years of Screening and Signaling

JOHN G. RILEY<sup>1</sup>

## 1. Introduction

WHY IS IT so hard to get a good price on a used car? Why is the annuity market so thin? Why do firms offer lower premiums per unit of coverage to insureds who accept deductibles? Why do firms continue to pay dividends, even though shareholders are subject to double taxation? Under what conditions can a monopoly profitably deter entry by setting a low “limit price” rather than the monopoly price? These are just a few of the vast array of questions that economic theory was in no position to answer until the development of new theoretical foundations.

With the benefit of hindsight, there were four pioneer papers that set the stage for an unprecedented research effort that continues to this day.<sup>2</sup> The remarkable paper by William Vickrey (1961) examined a range of issues in the provision of incentives when agents have private information. In the appen-

dix, Vickrey even provided a foundation for modern auction theory. Ten years later James Mirrlees (1971), in his analysis of optimal income taxation, provided subtle insights into the trade-off between efficiency (the incentive to work) and redistribution. Around the same time, George Akerlof (1970) showed how trade can almost completely collapse when agents on one side of a market know only the distribution of product quality, rather than the quality of each item traded.<sup>3</sup> Finally Michael Spence (1973) asked whether, in a competitive marketplace, sellers of above-average quality products could “signal” this fact by taking some costly action. On the other side of the market, could the uninformed buyers use the costly action as a way to “screen” for quality?

In today’s terminology, the papers by Vickrey and Mirrlees focussed on the design of an incentive scheme by an imperfectly informed monopolist. Despite having an informational disadvantage, it is typically the case that the monopolist has an incentive to offer a set of alternatives that (at least partially) separates out agents with different characteristics. In Mirrlees’ case, more able workers

<sup>1</sup> Department of Economics, UCLA. I am indebted to Sara Castellanos and Felipe Zurita for their assistance in the citation search, which served to guide the selection of articles to be included, and for their useful summaries. The extensive and most helpful comments and suggestions of Hongbin Cai, Jack Hirshleifer, Beverly Lowe, the editor, and three referees are also very gratefully acknowledged.

<sup>2</sup> Even long after all of these papers were written, the very strong links were not fully understood.

<sup>3</sup> As evidence of how unusual Akerlof’s ideas were perceived to be, his paper was rejected by two leading journals of the time.

choose to earn higher income even though they know they will pay higher taxes. And in a Vickrey auction, buyers with higher valuations have an incentive to bid higher. Akerlof and Spence examined models with a very similar formal structure. Imperfectly informed agents make offers, taking into account the heterogeneity on the other side of the market. However, there is a key difference. Instead of a single uninformed agent, there is now competition among such agents. Thus, while Vickrey and Mirrlees study optimal incentive schemes, Akerlof and Spence examine incentive schemes that will survive the competitive forces of the marketplace, that is, equilibrium incentive schemes.

One of the great theoretical controversies of this vast literature is the characterization of conditions under which equilibrium incentive schemes exist. This is a focus of section 2, which presents the basic theory of “screening.” Section 2 also considers situations in which an informed agent must first “signal” by taking a costly action, without observing the terms under which he will be able to trade. The critical question is then how uninformed potential trading partners will interpret the informed agent’s action. Such a model can only have strong predictive power if it is possible to place strong restrictions on equilibrium beliefs.

Additional theoretical subtleties are examined in section 3. The next four sections look at many of the key applications of the theory and attempt to test the theory.<sup>4</sup> Section 4 focuses

on applications in industrial organization, section 5 in labor markets, and section 6 in finance. Section 7 provides a brief introduction to related papers in macroeconomics.

## 2. Introduction to the Theory

### 2.1 Hidden Knowledge and Adverse Selection

Central to traditional equilibrium theory is the idea that an economy guided by prices economizes on information. In a private goods world, individual agents need to know nothing about the other agents in the marketplace, and yet Walrasian equilibrium prices result in a Pareto-Efficient allocation. Critical to the ideal functioning of the invisible hand, however, is the requirement that agents have the same information about the characteristics of the commodities being traded. When this assumption fails, how to take full advantage of the potential gains to trade becomes a much more subtle issue.

Akerlof (1970) provides the first formal model, illustrating how dramatically asymmetric information can affect equilibrium trades. Consider a population of car owners, each of whom must choose whether to purchase a new car or hold onto the old one. While used cars look alike to potential buyers, the actual quality varies. Only the current owner knows the actual quality of his car. From the experience of prior periods, buyers correctly anticipate the average quality of used cars that are traded. The market price of a used car thus reflects the average quality of a car on the market. If quality differences are large, those with cars of sufficiently high quality find it better to keep their old cars rather than sell, thereby lowering the average quality of cars being traded. As Akerlof emphasized, this incentive to withdraw from the market can lead to

<sup>4</sup>The reader who is primarily interested in a particular applied field may wish to go directly from section 2 to the appropriate later section. In almost every field, the literature is just too large to survey comprehensively. A primary criterion for selecting one paper to comment upon and not another was the interest generated by the paper as measured by its citation count in the Social Science Citation Index.

an equilibrium in which none but the very worst cars (the “lemons”) are traded.

To understand this, consider a stripped-down version of Akerlof’s model. The market value of a car of quality  $t$  is  $V(t) = \alpha + \beta t$ , where  $t$  is uniformly distributed on  $[0,1]$ . Given the uniform distribution, the average quality of used cars that are of quality  $t$  or lower is  $\bar{V}(t) = \alpha + \frac{1}{2}\beta t$ . Suppose that the expected consumer surplus from the purchase of a new car is  $s$ . Suppose also that only those used cars of quality  $t'$  or lower are traded. Then the average market value of these cars is  $\bar{V}(t')$ . If a type  $t$  seller holds on to his used car then his payoff is  $V(t)$ . If he sells, he gets the consumer surplus associated with the purchase of a new car and, for his used car, a price equal to the average market value of such cars,  $\bar{V}(t')$ . Thus, his total payoff from selling his old car and buying a new one is  $\bar{V}(t') + s$ . Type  $t$  is therefore better off holding on rather than selling if and only if  $V(t) > \bar{V}(t') + s$ , that is,  $\beta(t - \frac{1}{2}t') > s$ . In equilibrium, the marginal seller must be just indifferent between holding and selling. Thus type  $t'$  is the equilibrium marginal seller if  $\frac{1}{2}\beta t' = s$ . All those with higher quality cars are better off opting out of the market.

In the limiting case, when  $s/\beta$  is very small, it follows that the marginal type  $t'$  is small. Therefore the market for used cars essentially dries up, with only the very low-quality cars being traded. While such an extreme outcome is possible, the important observation is that it is the sellers of the higher quality items who opt out of the market. Asymmetric information therefore adversely affects both the volume and quality of the items traded.

This phenomenon has long been understood by the insurance industry. Consider, for example, the purchase of an annuity upon retirement. While an insurance company can check current health, the customer (the seller of the risk) knows

more about family longevity than the insurance company (the buyer of the risk.) The sellers with the greatest longevity stand to gain the most from the annuity since they expect a longer stream of payments. But, from the viewpoint of the buyers, these are the bad risks since they will cost the most. As a result, annuities are expensive and the market is thin.

Obviously, a necessary condition for such a market failure is that the cost of establishing a reputation for honesty is too high. Development economists have noted that such problems tend to be more prevalent in economies where market institutions are more decentralized, and there are large numbers of direct sales by small sellers.<sup>5</sup> In more highly developed markets, it is the low frequency of trades by any single seller that makes reputation-building prohibitively costly.

We now illustrate adverse selection more formally in a richer model of insurance. An insurance contract  $X = (r, m)$  is an agreement by the insurer that in return for receiving a premium  $m$  it will provide coverage  $r$  in the event of a loss  $L$ . Let  $p_t$  be the probability of loss for a type  $t$  individual. For simplicity, suppose that  $t \in \{1, 2\}$  and that the higher indexed type is a better risk (lower loss probability.) Given an initial wealth  $W$ , and strictly concave von Neumann-Morgenstern utility function  $v(\cdot)$ , expected utility of type  $t$  is

$$U_t(X) = U_t(r, m) = (1 - p_t)v(W - m) + p_tv(W - L + r - m).$$

It is readily confirmed that expected utility is a strictly concave function of the contract terms  $X = (r, m)$ . The indifference curve for each type through the contract  $\hat{X}$  is depicted in figure 1.<sup>6</sup> The slope of this indifference curve is the marginal willingness to pay an additional

<sup>5</sup> See, for example, Robert Klitgaard (1991).

<sup>6</sup> For consistency with later diagrams, the axes have been inverted in this figure.

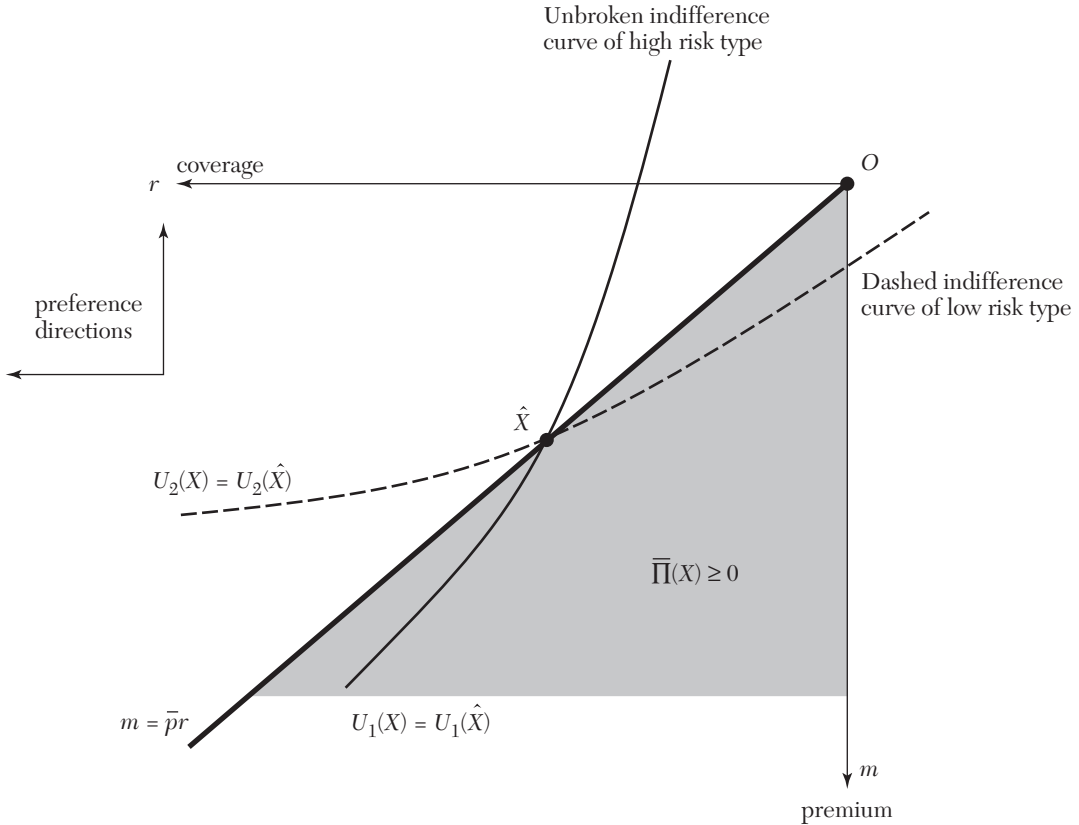


Figure 1. Single Crossing Property and Adverse Selection

premium as the coverage increases. Intuitively, the lower the probability of loss, the smaller the additional premium an individual is willing to pay for greater coverage. Thus, the dashed indifference curve of the low-risk type is flatter than the unbroken indifference curve of the high-risk type.<sup>7</sup> As we shall see, this

<sup>7</sup> It is readily confirmed that the slope of the indifference curve at  $X = (m, r)$

$$\begin{aligned} \left. \frac{dm}{dr} \right|_{\bar{U}_t} &= - \frac{\frac{\partial U_t}{\partial r}}{\frac{\partial U_t}{\partial m}} \\ &= \frac{p_t v'(W - L + r - m)}{p_t v'(W - L + r - m) + (1 - p_t) v'(W - m)}, \end{aligned}$$

increases with  $p_t$ . Note also that the slope exceeds  $p_t$  if and only if coverage is incomplete.

“single-crossing property” of the preference maps of different types is absolutely central to models of informational asymmetry.

Let  $\bar{p}$  be the probability of loss averaged over the good and bad risks. Ignoring administrative expenses, the expected profit on the contract  $X = (m, r)$  for an individual selected at random from the population is then

$$\begin{aligned} \bar{\Pi}(X) &= m - \bar{p}r. \\ \text{Expected profit} &= \text{premium} - \text{probability of loss} \times \text{coverage} \end{aligned}$$

In figure 1, expected profit  $\bar{\Pi}(X)$  is positive in the interior of the shaded region below the zero profit line  $m = \bar{p}r$ . Note that the indifference curve of the low-risk group is sufficiently flatter that

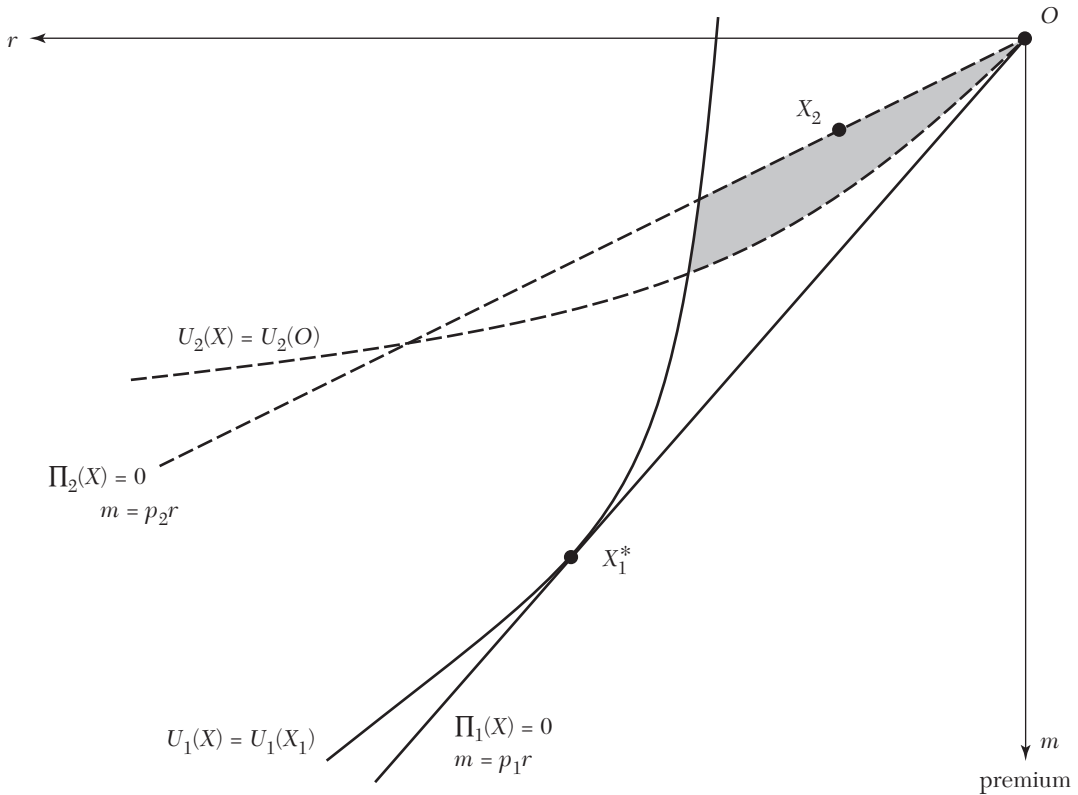


Figure 2. Single Crossing and Screening

it lies below the no-insurance point  $X = (0,0)$ .<sup>8</sup> Thus, low-risk types choose not to insure, leaving only the high-risk types. This is another illustration of Akerlof's lemons principle. However, there is now a continuum of possible levels of coverage. A complete analysis thus requires that we consider different levels of coverage. We begin by supposing that adverse selection has taken place and that the high-risk types are the only ones getting insurance. Given competition among insurance companies (and assuming insurance companies are risk neutral), the equilibrium contract  $X_1^*$  is the utility-maximizing zero profit

<sup>8</sup> If the loss probabilities are similar, the indifference curve lies above the origin. Thus, for adverse selection to occur, the range of loss probabilities must exceed some threshold level.

contract for a high-risk type.<sup>9</sup> This is depicted in figure 2.

As in the previous figure, indifference curves (and the zero-profit line) for the low-risk type are shown as dashed curves. Note that the dashed indifference curve for the low-risk type  $U_2(X) = U_2(O)$  goes through the no-insurance point  $O$  and lies above the contract  $X_1^*$ . Thus, the low-risk types are indeed better off out of the market than purchasing the insurance contract  $X_1^*$ .

### 2.2 Screening

We will now argue that insurance companies have an incentive to “screen” for low-risk types by offering a second

<sup>9</sup> That is,  $X_1^* = \arg \text{Max}_X \{U_1(X) \mid \Pi_1(X) \geq 0\}$ .

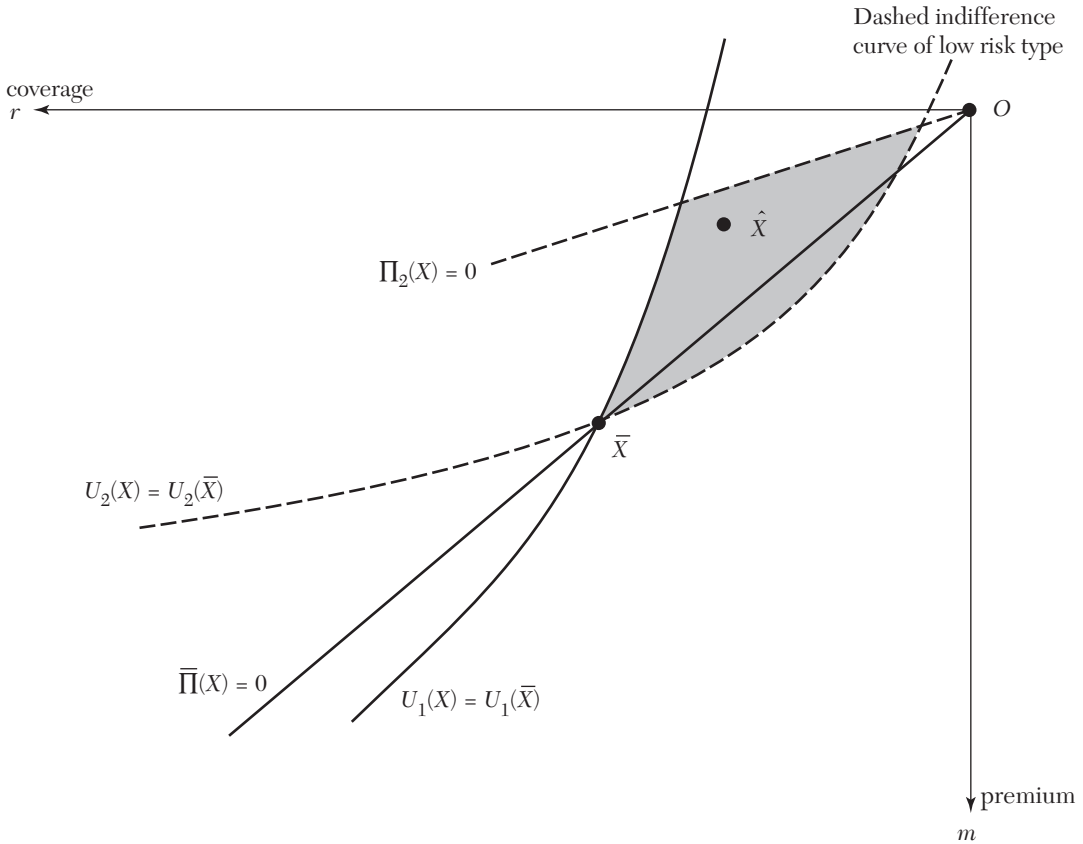


Figure 3. No Pooling Nash Equilibrium

insurance policy that provides lower coverage. Consider the contracts in the interior of the shaded area in figure 2. These lie below the indifference curve  $U_1(X) = U_1(\hat{X}_1^*)$  and above the indifference curve  $U_2(X) = U_2(O)$ . Thus, they are attractive only to the low-risk types. Moreover, they also lie below the zero expected profit line  $\Pi_2(X) = 0$  for the low-risk group. Thus any such contract screens for the low-risk types and is strictly profitable.

Consider next the insurance contract  $X_2$  on the zero profit line  $\Pi_2(X) = 0$  bounding the shaded region of profitable screening. Spence (1973) in his seminal thesis argued that pairs of contracts such as  $X_1^*$  and  $X_2$  were informa-

tionally consistent equilibrium contracts. If firms offer these two contracts based on the belief that types will separate, then these expectations are fulfilled. Moreover, the expected profit on each contract is zero. Of course, exactly the same argument holds for all points on the upper boundary of the shaded region. This led to Spence's controversial conclusion that there was a continuum of informationally consistent equilibria.

While the idea of an informationally consistent set of contracts appears to be a natural generalization of Walrasian equilibrium, it is incomplete in a number of ways. First, there is no competition in the screening dimension. Second, the timing of actions is not spelled out.

Third, the information sets of the agents are not fully specified. These issues were independently addressed by Riley (1975) and Michael Rothschild and Joseph Stiglitz (1976). The latter paper makes a more radical departure from Spence's analysis by proposing that the model should be viewed as a noncooperative game between the uninformed insurance companies and the consumers.

### 2.3 Rothschild-Stiglitz Screening Game<sup>10</sup>

The game is defined thus: First, the uninformed players announce offers. Second, each informed type chooses the offer which is best for him. The offers are a Nash equilibrium set of contracts if, given the strategies of the other players, each uninformed agent's strategy is a best response.

The three key conclusions about the (pure strategy) Nash equilibria of this game are that: (i) different types are always separated, (ii) there is at most one separating equilibrium, and (iii) equilibrium exists if and only if the proportion of high-value (low-risk) types is sufficiently low. We now look at each of these points in turn.

#### 2.4 No Pooling

It is easy to see that there can be no Nash equilibrium that pools the different types. Consider figure 3 and suppose that the contract  $\bar{X}$  is a Nash equilibrium. If it were strictly profitable, an insurance company could offer a slightly smaller premium and attract everyone in the pool. Then  $\bar{X}$  must just break even. It follows that the flatter zero-profit line for the low-risk type,

<sup>10</sup> In the early literature, the terms "screening" and "signaling" are used almost interchangeably. More recently, it has become common to refer to the game in which the uninformed agents move first as a "screening game" and a game in which the informed agents move first as a "signaling game." We shall follow this convention.

$\Pi_2(X) = 0$ , must be as depicted. Note that any offer such as  $\hat{X}$ , in the interior of the shaded region, is preferred over  $\bar{X}$  by only the low-risk type. Since such offers also lie below  $\Pi_2(X) = 0$ , they are strictly profitable. We have therefore shown that it is always profitable and feasible for an insurance company to screen and "skim the cream" from the pool.

#### 2.5 Uniqueness

We now show that there is at most one Nash equilibrium pair of contracts. The informationally consistent contract pair  $(X_1^*, X_2)$  from figure 2 is redrawn in figure 4. Consider the insurance contract  $\hat{X}$ . Low-risk types are strictly better off choosing  $\hat{X}$  rather than  $X_2$ , while high-risk types strictly prefer  $X_1^*$  over  $\hat{X}$ . Thus, the new offer successfully screens for the low-risk types. Since  $\hat{X}$  also lies below the zero-profit line for the low-risk types, it is strictly profitable. Then the pair of contracts  $(X_1^*, X_2)$  is not a Nash equilibrium. Exactly the same argument holds for any point to the northeast of  $X_2^*$  on the zero-profit line bounding the shaded region. Thus, if there is a Nash equilibrium, it must be the pair  $(X_1^*, X_2^*)$ . Combining these arguments, we have shown that if there is an equilibrium  $(X_1^*, X_2^*)$  it has the following properties: (i)  $X_1^*$  is the best zero-profit contract for the high-risk types, and (ii)  $X_2^*$  is the best zero-profit contract for the low-risk types, which is just separating.<sup>11</sup>

#### 2.6 Equilibrium

Thus far we have established that if there is an equilibrium it must be the separating pair of contracts with the minimum separation of the two types. The final step is to determine conditions under which there are no profitable defections from these contracts. Rather than

<sup>11</sup> This conclusion generalizes immediately to the  $n$  type case.

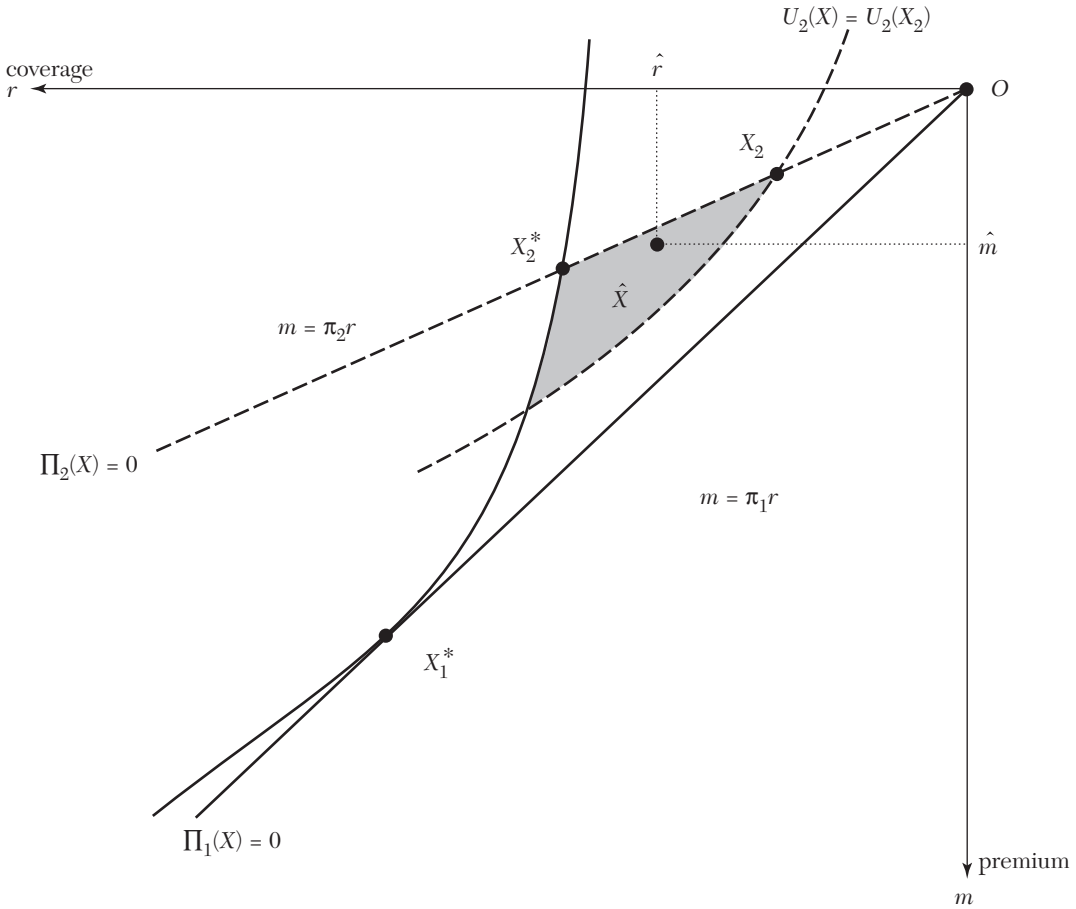


Figure 4. Minimum Separation of Types

continue with the insurance example, it will be convenient to switch to a simple version of Spence's labor market model. A type  $t$  individual has a productivity of  $V_t(z)$ <sup>12</sup> which is increasing in both his type and his level of education,  $z$ . An employment contract  $X = (z, w)$  is an agreement to pay a wage  $w$  to an in-

dividual with education level  $z$ . The worker's utility  $U_t(X) = U_t(z, w)$  is an increasing function of  $w$  and a decreasing function of  $z$ . Formally this model is identical in structure to the insurance model. However, for expositional reasons, we follow Spence and make the further assumption that utility can be expressed in the separable form  $U_t(z, w) = w - c_t(z)$ . Then the slope of an indifference curve for type  $t$  is:

$$\left. \frac{dw}{dz} \right|_{\bar{u}_t} = - \frac{\frac{\partial U_t}{\partial z}}{\frac{\partial U_t}{\partial w}} = c'_t(z).$$

<sup>12</sup>While the literature simply takes marginal product as given, the model is readily generalized. Let  $V_t(z)$  be the number of efficiency units of labor supplied by a type  $t$  worker. Then if the firm hires  $L_f$  efficiency units of labor, and the output price is  $p$ , the marginal value product of a type  $t$  worker is  $V_t(z) \equiv pMP_L(L_f)v_t(z)$ . Assuming price-taking behavior, the firm adds workers until the marginal value product of type  $t$  is equal to his market wage  $w(z_t)$ .

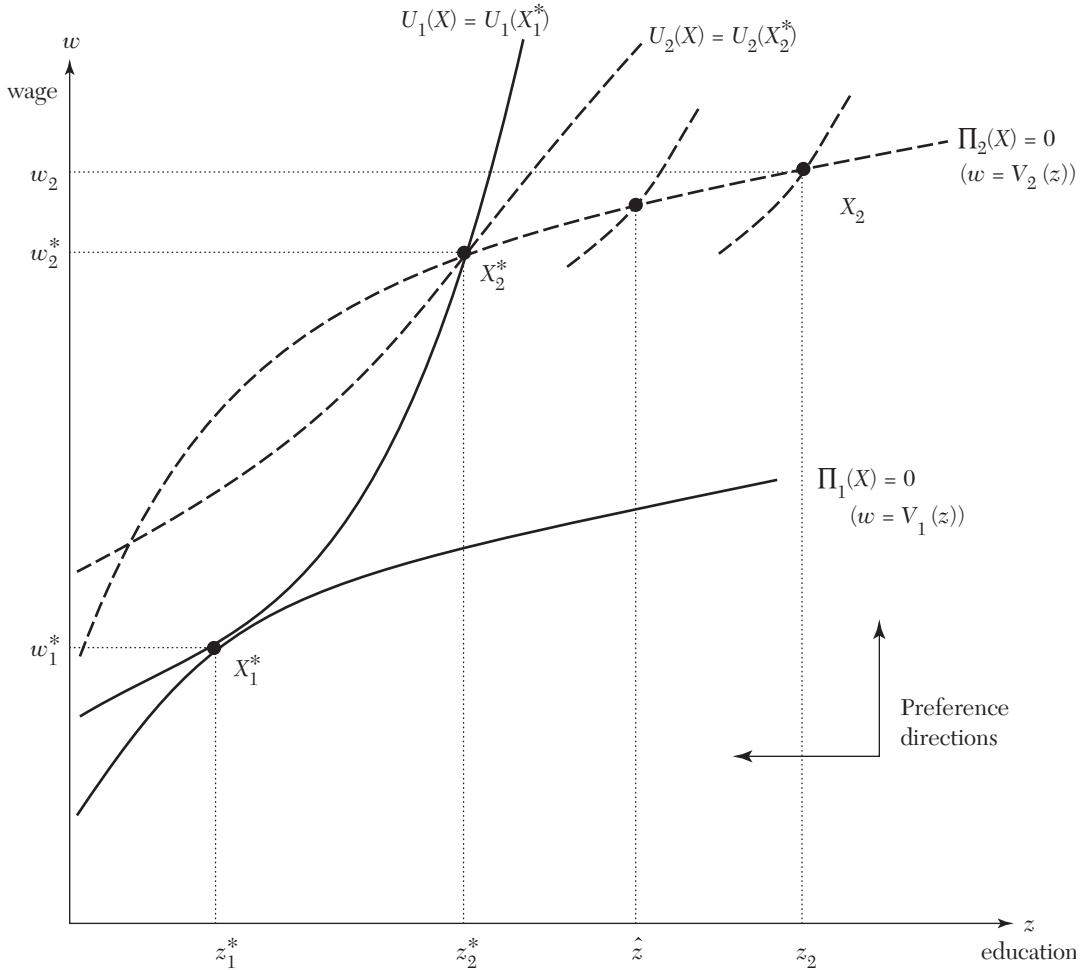


Figure 5. Labor Market Screening

The single-crossing property holds if the marginal cost of education is lower for more productive workers. This is depicted in figure 5 for the simplest case of two types.

In graphical terms, the dashed indifference curves of a high-productivity (type 2) worker are flatter. Given our assumptions, the profit on a type  $t$  worker who accepts the contract  $(z, w)$  is  $\Pi_t(X) = V_t(z) - w$ . The zero profit curves are also depicted in figure 5. The analysis then proceeds exactly as in the insurance example. The only potential Nash

equilibrium is that in which the low productivity worker is offered his best zero-profit contract and the level of the educational screen is set just high enough to deter low-productivity workers. These two contracts  $X_1^*$  and  $X_2^*$  are as depicted in figure 6.

To complete the analysis, we need to ask whether the unique candidate pair of contracts  $X_1^*$  and  $X_2^*$  is a Nash equilibrium. Figure 6 provides the answer. As depicted, the equilibrium indifference curve for the high-quality workers cuts below the zero-expected profit line for

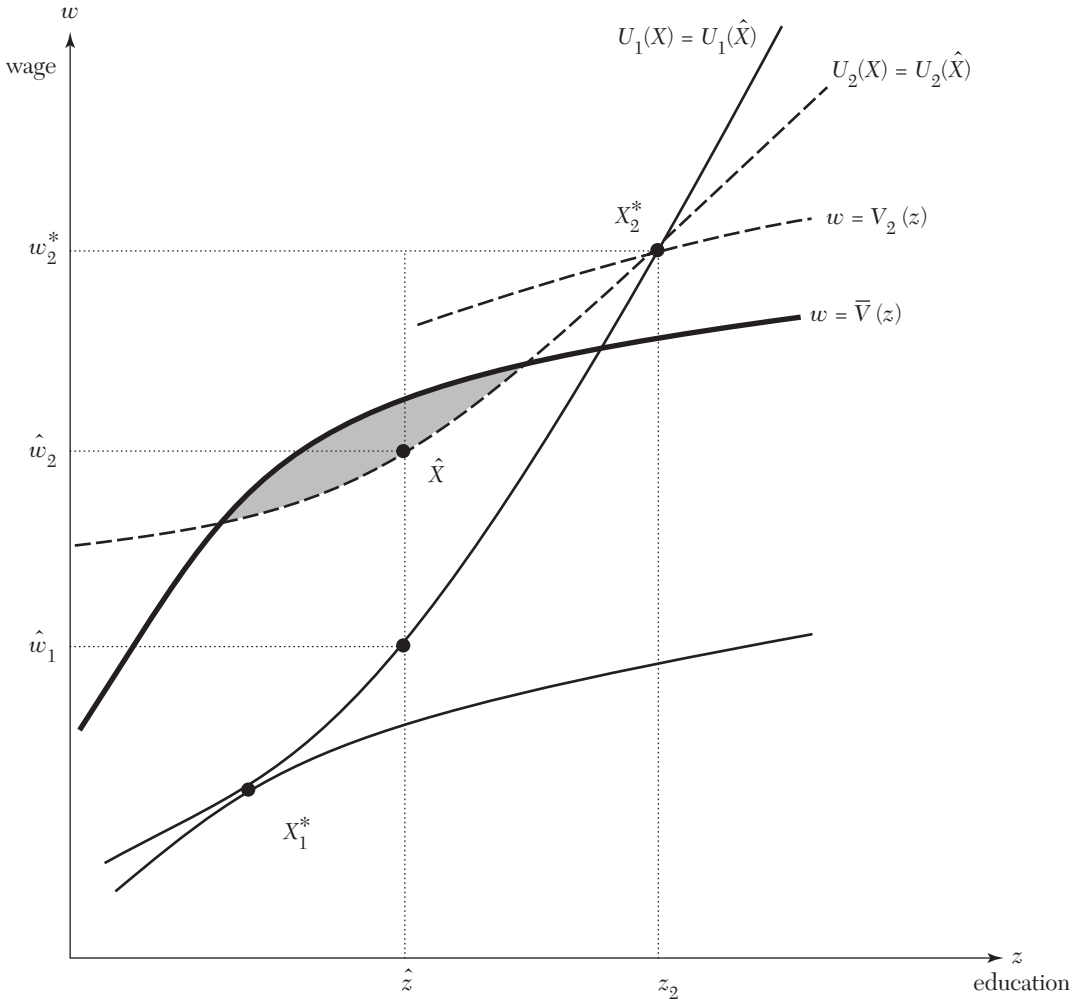


Figure 6. Nonexistence of a Screening Equilibrium

a worker drawn at random from the entire population. Note that this will be the case if and only if the fraction of high-quality workers is sufficiently high. For then the curve  $w = \bar{V}(z)$  lies just under the corresponding curve for the high-quality workers  $w = V_2(z)$ . All contracts in the interior of the shaded region are strictly preferred by both types of worker and generate strictly positive expected profits. Thus, the separating pair of contracts,  $X_1^*$  and  $X_2^*$  is not a Nash equilibrium. Therefore, as empha-

sized by Rothschild and Stiglitz, a necessary and sufficient condition for equilibrium is that the proportion of high-quality workers should not be too high.

Riley (1985) extends the analysis by asking what sort of assumptions about preferences are sufficient for equilibrium. Suppose that we fix the technology, the distribution of types and the preferences of low-quality workers. Consider the contract  $\hat{X}$  in figure 6. This lies below the curve  $w = \bar{V}(z)$  if and only

if the vertical distance  $w_2^* - \hat{w}_2$  is sufficiently large relative to  $w_2^* - \hat{w}_1$ . But the contracts  $X_2^*$  and  $\hat{X}$  lie on the same indifference curve for a high productivity type. Thus,

$$\begin{aligned} U_2(z_2^*, w_2^*) &= w_2^* - c_2(z_2^*) \\ &= \hat{w}_2 - c_2(\hat{z}_2) = U_2(\hat{z}_2, \hat{w}_2), \end{aligned}$$

and therefore  $w_2^* - \hat{w}_2 = c_2(z_2^*) - c_2(\hat{z}_2)$ . A symmetrical identical argument for type 1 workers establishes that  $w_2^* - \hat{w}_1 = c_1(z_2^*) - c_1(\hat{z}_1)$ . Therefore

$$\frac{w_2^* - \hat{w}_2}{w_2^* - \hat{w}_1} = \frac{c_2(z_2^*) - c_2(\hat{z}_2)}{c_1(z_2^*) - c_1(\hat{z}_1)}.$$

We have argued that equilibrium fails to exist if and only if the left-hand side is sufficiently large. Thus, for equilibrium, the ratio of educational costs must be sufficiently small. This will be the case if the marginal cost of education is sufficiently lower for the high quality type. The central conclusion is that it is not enough for preferences to satisfy the single crossing property. Instead, the preference maps of the different types should vary sufficiently rapidly with type.

### 2.7 Monopoly Screening

With a single uninformed agent, the optimal screening mechanism is superficially very similar. Consider our labor market example once more. Suppose there is a small supply of low-productivity workers so that the monopolist maximizes profit by hiring both types of worker. For simplicity, suppose both types have the same reservation wage  $w_R$ . The monopolist maximizes profit on type 1 workers by maximizing profit,  $\Pi_1(z, w) = V_1(z) - w$ , subject to the constraint that  $U_1(z, w) \geq w_R$ . This is the contract  $X_1$  in figure 7.

To be incentive compatible, a high-quality (type 2) worker must be at least indifferent between the offer he ac-

cepts and  $X_1$ . Thus his offer must be on or above the heavy dashed indifference curve. The monopolist then maximizes profit on a type 2 worker  $\Pi_2(X) = V_2(z) - w$  subject to the constraint that  $U_2(X) \geq U_2(X_1)$ .

Note that at  $X_t$ ,  $t = 1, 2$ , the slope of the indifference curve  $c'_1(z)$  is equal to the slope of the iso-profit curve  $V'_t(z)$ . Thus both contracts are efficient. We will now argue that the monopolist can always do better by lowering the educational requirement for the low type. The resulting pair of contracts is  $X_1^M$  and  $X_2^M$ . Note that this change reduces the profit on low-productivity workers and raises the profit on high productivity workers. But, starting from the contract  $X_1$  and moving around the type 1 reservation indifference curve, the iso-profit curve and indifference curves are locally of the same slope. Thus, in the neighborhood of  $X_1$ , the loss in profit on a type 1 worker is of second order, while the gain in profit on a type 2 worker is of first order.

As is the case for the R-S screening model, the monopolist maximizes profit by separating low- and high-quality workers. However, there is an important difference. Note that now it is the high-productivity worker who is offered an efficient contract while the low-productivity worker achieves a sub-optimal education. The opposite conclusion holds for the Nash equilibrium of the R-S screening game. In the monopoly model, the firm sacrifices efficiency at low-quality levels in order to extract more surplus from high-productivity workers. In the "competitive" screening model, firms sacrifice efficiency at high-quality levels in order to separate high- from low-quality workers.

The earliest formal modeling of monopoly screening is Mirrless' (1971) remarkable paper on income taxation.

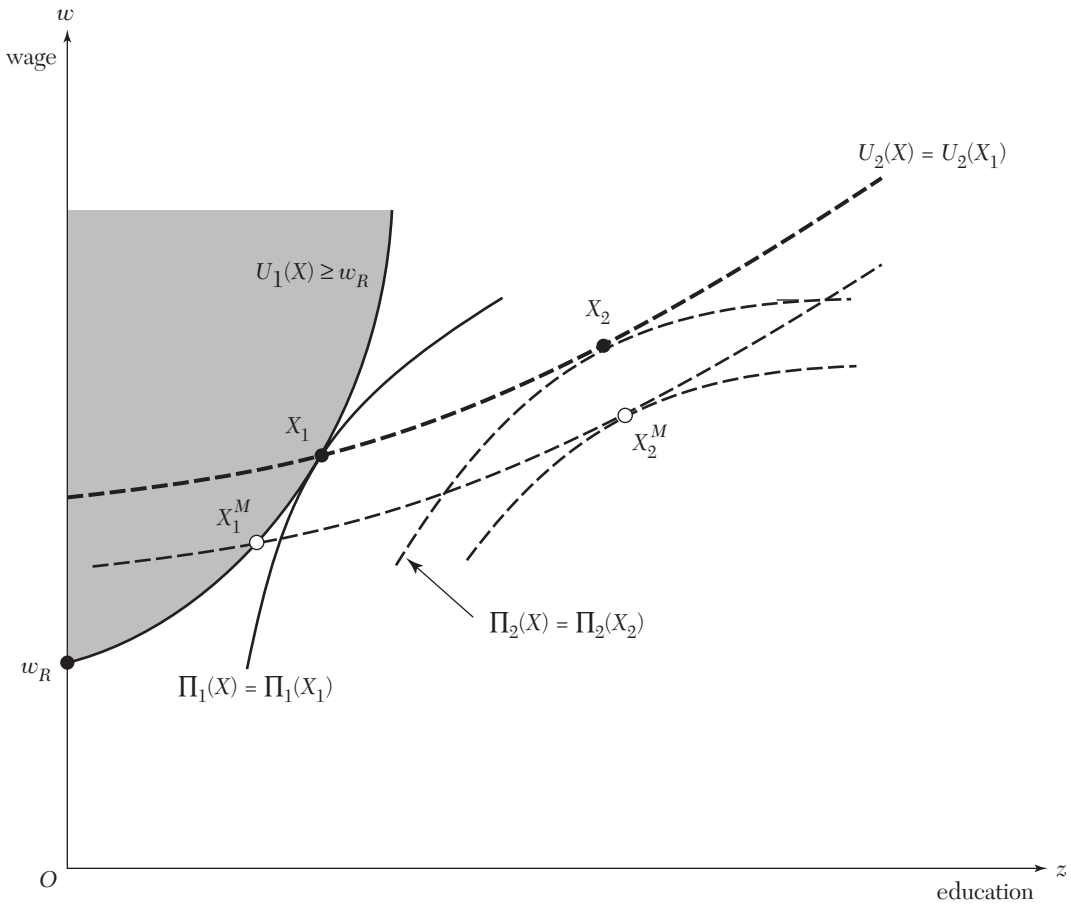


Figure 7. Monopoly Screening

Suppose we reinterpret the vertical axis of figure 7 as gross income and the horizontal axis as tax. Then, as Mirrlees observed, the trade-off between income and taxation differs, because individuals of differing ability have different opportunity costs of leisure. Then the tax authority chooses among incentive compatible tax-income pairs  $(X_1, X_2)$  to achieve its social objective. This paper and the closely related work by Vickrey (1961) on auction choice has since spurred a vast literature on the design of incentive schemes by an uninformed “principal.” Much of this literature has at its core the single crossing property.

### 2.8 Signaling

In the R-S screening model, it is the uninformed agents who have the critical role. They use their knowledge of differences in preferences to screen for different quality levels. The informed agents simply respond to the offers made by the uninformed. But what if it is the informed agent or agents who must move first? For example, what if a firm has developed a new product or service whose quality is not easily evaluated by potential buyers? Is there some way that the firm can, through a costly action, “signal” to buyers that it is selling a high-quality product?

To answer these questions, we return to Spence's labor market model and explore the implications, under the new assumption that it is the informed agent who must move first.<sup>13</sup> In this signaling game, firms are seeking to hire a new type of technology consultant who may be of high or low quality. Consider figure 5 once more and the pair of education levels  $z_1^*$  and  $z_2$ . Suppose that the consultant's strategy is to choose the higher education level if and only if his quality is high. If firms believe this, it is a Nash-equilibrium best response to pay a wage equal to the perceived marginal product. Thus a consultant with education level  $z_1^*$  is offered a wage  $w_1^* = V_1(z_1^*)$ , while a consultant with education level  $z_2$  is offered a wage  $w_2 = V_2(z_2)$ . Given such offers, it is clear from figure 5 that the consultant is better off choosing the higher education level if and only if he has a high marginal product. The pair of contracts  $X_1^*$  and  $X_2$  are thus Nash equilibrium contracts. By the same argument, there is a continuum of equilibria with the high-quality contract lying on the curve  $\Pi_2(X) = 0$ , between  $X_2$  and  $X_2^*$ . Indeed, as In-Koo Cho and David Kreps (1987) showed, all the equilibria discussed by Spence are Bayesian-Nash equilibria of this game.

With the better-informed agent moving first, the critical issue is how a less-informed agent will respond to some unanticipated action by the first mover. Unfortunately, there is nothing in the formal description of a Nash equilibrium to restrict such beliefs. One of the key innovations of modern game theory is the development of ways to "refine" beliefs. Among the least controversial of these ideas is that the equilibrium be

"sequential" (Kreps and Robert Wilson 1982). In the signaling game, this requires that the second movers assign a probability distribution over types for every possible action by the first mover and, hence, a best response  $w_{br}(z)$  to every feasible signal  $z$ . Given these best responses, the Nash equilibrium is sequential if the first mover has no incentive to change his strategy. Consider then the Nash equilibrium strategies  $z_1^*$  and  $z_2$  in figure 5. If firms believe that low productivity consultants are sufficiently more likely to take some out-of-equilibrium level of the signal  $z$ , the best responses will be low wage offers. Given these low wage offers, it follows that a high quality consultant is worse off deviating. Thus, there is a continuum of (sequential) Nash equilibria.

Cho and Kreps (1987) argue that out-of-equilibrium beliefs should be further refined. If a consultant takes an out-of-Nash-equilibrium action  $\hat{z}$ , then firms go through the following "intuitive" exercise.

- (1) If all the uninformed firms believe it is a type  $t$  consultant who chose  $\hat{z}$ , what will be the highest wage offered? Let the resulting contract be  $\hat{X} = (\hat{z}, \hat{w})$ .
- (2) Would a type  $t$  consultant be strictly better off with the contract  $\hat{X}$  than with his Nash equilibrium contract?
- (3) Is it also the case that no other type would be better off switching to contract  $\hat{X}$ ?

If the answer to both (2) and (3) is yes, Cho and Kreps argue that a type  $t$  consultant has an incentive to deviate. That is, the pair of contracts  $X_1^*$  and  $X_2$  fails their "intuitive criterion."

In figure 5, any education level  $z_2$  strictly greater than  $z_2^*$  fails the intuitive criterion. If firms believe that the deviation to  $\hat{z}$  is by a high-quality consultant, they will bid his wage up to  $w = V_2(\hat{z})$ .

<sup>13</sup> We will consider signaling games in which there is more than one uninformed agent. Having only a single agent changes the outcome, but not the method of analysis.

This is strictly preferable for a high-quality consultant, but strictly worse for a low-quality consultant. Thus, the belief that it is a high-quality consultant is sustained.

Similar arguments establish that there can be no pooling equilibrium when the intuitive criterion is applied. Thus the unique Nash equilibrium pair of contracts, which also satisfies the intuitive criterion, is the pair  $X_1^*$  and  $X_2^*$ .

The intuitive criterion has dominated the literature in the years since its introduction. From the perspective of applied research, it is easy to understand why. Gone are the problems of non-existence that make applied theorists uneasy about the Rothschild-Stiglitz game. Gone also is the continuum of sequential Nash equilibria. Instead, given the single-crossing property, the theory yields a well-specified prediction of full separation of types. Unfortunately, the theory is not as tidy as it might appear. Consider figure 6. Applying the intuitive criterion yields the unique separating equilibrium contracts  $X_1^*$  and  $X_2^*$ . Suppose the consultant deviates and chooses education level  $\hat{z}$ . Suppose also that there is only a very small probability that the consultant is of low quality. Then the heavy curve  $w = \bar{V}(z)$  representing the average productivity across the two quality levels is extremely close to the high-quality zero profit curve  $w = V_2(z)$ . How will firms respond to such a deviation? Sanford Grossman and Motty Perry (1986) argue as follows. Let  $T$  be the set of all types (here  $T = \{1,2\}$ ) and let  $S$  be some subset of  $T$ . In the spirit of the intuitive criterion, the following questions need to be asked.

- (1) If all the uninformed firms believe it is a type from  $S$  who chose  $\hat{z}$ , and update their beliefs using Bayes Rule, what will be the highest wage

offered? Let the resulting contract be  $\hat{X} = (\hat{z}, \hat{w})$ .

- (2) Would any consultant of type  $t \in S$  be strictly better off with the contract  $\hat{X}$  than with his Nash equilibrium contract?
- (3) Is it also the case that no other type would be better off switching to contract  $\hat{X}$ ?

If the answer to both (2) and (3) is yes, Grossman and Perry (G-P) argue that a consultant whose type is in  $S$  indeed has an incentive to deviate. Of course, if the subset  $S$  is a singleton, the G-P criterion reduces to the intuitive criterion.

In figure 6, let the subset  $S$  be both types. As long as the probability of a high type is sufficiently high, there is a shaded region of profitable responses which are strictly preferred by both types. Thus the unique Cho-Kreps equilibrium fails the G-P criterion. It follows that there is no equilibrium satisfying the G-P criterion. Indeed, an equilibrium of the signaling game fails to exist in precisely those situations where there is no equilibrium of the Rothschild-Stiglitz screening game.

My view on all of this is that it is very hard to make a case in favor of the Cho-Kreps criterion without also providing support for the more stringent G-P criterion. Since I find the intuitive criterion persuasive, I am unable to reject the G-P criterion. I am therefore forced to conclude that there will not always be a credible equilibrium. This should not be too surprising. In traditional equilibrium theory, problems for equilibrium often occur whenever there are externalities. Here it is the preferences of the low-quality types which constrain the profitable alternatives of higher quality types. The more similar are the preferences of the two types, the greater the negative informational externality. As we have already seen, it

is possible to characterize conditions under which there exists a separating equilibrium under the more stringent G-P criterion. The critical requirement is that the rate at which the marginal cost of signaling declines with quality must be sufficiently high.

### 3 Further Theoretical Developments

#### 3.1 Screening with Many Types

One of the limitations of the basic model is the assumption that there are only two types. It is natural to ask whether the difficulties are compounded as the number of types increases. To illustrate the issues involved, we focus on a simple labor market example in which there is a continuum of types. Consider the R-S screening game. Suppose that productivity of type  $t$  is  $V(t)$ , that is, the signal has no direct effect on productivity. Suppose also that types are continuously distributed with support  $[\alpha, \beta]$ . The cost of an education level  $z$  is  $C(t, z)$ , where the marginal cost of education is a decreasing function of type.

As in the two-type case, it is not difficult to characterize the equilibrium (assuming it exists.) First, arguing as in the two-type case, there can be no equilibrium pooling. We then seek a separating equilibrium. Given a wage function  $w(z)$ , type  $t$  chooses his education level  $z^s(t)$  to maximize his payoff

$$U(t, z, w) = w(z) - C(t, z). \quad (1)$$

For complete separation,  $z^s(t)$  is strictly increasing and satisfies the first order condition,

$$w'(z^s(t)) - \frac{\partial}{\partial z} C(t, z^s(t)) = 0. \quad (2)$$

In equilibrium, the marginal profit on each type is zero. Thus, the wage that type  $t$  chooses must be equal to his marginal product; that is,

$$w(z^s(t)) = V(t) \quad (3)$$

To close the model we need to determine the signal chosen by the lowest type. But, we can argue exactly as with two types, that the only feasible education level for type  $\alpha$  is the full-information efficient level  $z^s(\alpha)$ .

We now establish that the separating wage function  $w(z)$  satisfying these conditions is not a Nash equilibrium.<sup>14</sup> Choose  $\hat{w}$  so that type  $t$  is indifferent between his separating contract  $(z^s(t), w(z^s(t)))$  and  $(z^s(\alpha), \hat{w})$ . That is,

$$U(t, z^s(\alpha), \hat{w}) \equiv \hat{w} - C(t, z^s(\alpha)) \\ = w(z^s(t)) - C(t, z^s(t)). \quad (4)$$

Given the single crossing property, such a wage offer is strictly preferred by all types less than  $t$ . Let  $\bar{V}(t)$  be the expected marginal product of types less than  $t$ . Substituting from equation (4), the expected profitability of this offer is

$$\bar{\Pi}(t) = \bar{V}(t) - \hat{w} = \bar{V}(t) - w(z^s(t)) \\ + C(t, z^s(t)) - C(t, z^s(\alpha)).$$

Differentiating by  $t$  and collecting terms,

$$\bar{\Pi}'(t) = \bar{V}'(t) - \left[ w'(z^s(t)) - \frac{\partial}{\partial z} C(t, z^s(t)) \right] \frac{dz^s}{dt} \\ + \left[ \frac{\partial}{\partial t} C(t, z^s(t)) - \frac{\partial}{\partial t} C(t, z^s(\alpha)) \right].$$

From the first order condition, (2), the first bracketed expression is zero. In the limit, as  $t$  approaches  $\alpha$ , the second bracketed expression is zero. Thus,

$$\bar{\Pi}'(\alpha) = \bar{V}'(\alpha) > 0.$$

Since  $\bar{\Pi}(\alpha) = 0$ , it follows that at the education level  $z^s(\alpha)$ , any wage which exceeds  $V(\alpha)$  and is sufficiently close generates positive expected profits.

This general nonexistence result is, at first sight, devastating to the theory.

<sup>14</sup> The argument below does not seem to have appeared in print. The result was discussed, however, in unpublished drafts of Riley (1975) and Rothschild and Stiglitz (1976).

However, the result hinges on the assumption that all types would enter the industry under full information. Suppose instead that there is an equilibrium threshold for the types who choose to signal. For example, suppose that each worker has a reservation wage  $w^R$  (an opportunity in some different industry). If this wage  $w^R = V(\gamma) > V(\alpha)$ , there is an interval of types  $[\alpha, \gamma]$  who are better off in the other industry. (Remember that, in a separating equilibrium, each type is paid his marginal product.) Then the lowest wage among those who choose to signal is  $V(\gamma)$ . It follows that raising the wage at  $z^s(\alpha)$  attracts all those who would otherwise accept the reservation wage. If this pool is sufficiently large, the offer loses money.

Thus far I have focused on the critical problem at the lower endpoint of the wage distribution. As long as this problem can be dealt with satisfactorily, it is possible to derive sufficient conditions for existence for a fairly general version of the basic Spencian model, with a continuum of types (Riley 1979b, 1985). The key insight is that there exists a Nash equilibrium, as long as the rate at which the marginal cost of signaling declines with type is sufficiently high. Moreover, this equilibrium is unique and completely separates the different types.

### 3.2 *Alternative Equilibrium Concepts*

Given the nonexistence results for the simple static model, Charles Wilson (1977) began the exploration for stationary points of a dynamic adjustment process. He noted that if new profitable offers lead to losses for other offers, the latter might be quickly withdrawn. Based on this idea, he then weakened the Nash Equilibrium concept by requiring that any new offer remain profitable after the withdrawal of loss-making offers. A set of contracts  $W$  is a Wilson equilib-

rium if, for any additional offer  $X$  (or set of offers) that is strictly profitable, when the full set of offers is  $W \cup X$ , the new offer loses money when unprofitable offers in  $W$  are dropped. Wilson proved a general existence result and showed that, whenever there is no Nash separating equilibrium, the Wilson equilibrium (i) has fewer offers than types so there is some pooling and (ii) Pareto dominates any fully separating set of zero-profit contracts.

A similar argument along these lines produces a quite different result. In a reactive equilibrium, firms react by adding new profitable contracts rather than dropping old ones. Starting from a separating set of zero-profit contracts, any additional offer,  $X$ , involves pooling of different types. But, if the pool is profitable, profits on the best in the pool are even more profitable. As Riley (1979) showed, there are always screening reactions that skim the cream and result in losses for the offer  $X$ . A set of offers,  $R$ , is a reactive equilibrium, if, for any additional offer  $X$  that is profitable, that contract loses money when firms add profitable "reactive" offers. It turns out that the Pareto dominating set of separating zero-profit contracts is the unique reactive equilibrium.

Rather than weaken the equilibrium concept, Martin Hellwig (1987) changes the rules of the game. He shows that the Wilson equilibrium is a Nash Equilibrium of a game in which the uninformed have two rounds of play. In the first round each uninformed agent offers as many contracts as he wishes. The full set of contracts is then made public. In the second round each uninformed agent then has an opportunity to withdraw as many of his first round offers as he wishes. The informed agents then select from the set of contracts remaining after the second round. At least for the two-type case, it is easy to see that the

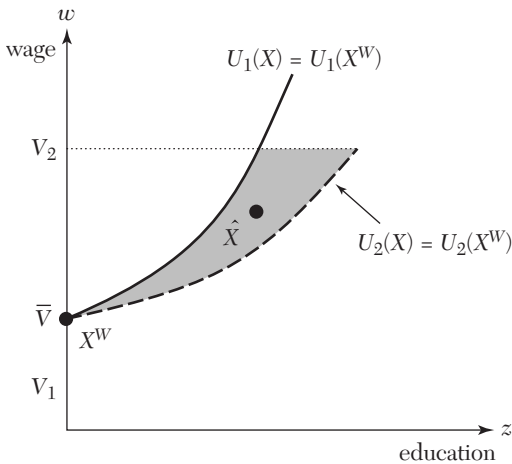


Figure 8. Wilson Equilibrium

Wilson equilibrium is a Nash equilibrium of this two-round game. Consider the case of two firms. The marginal product of type 2 is  $V_2$  and the expected marginal product of a worker drawn randomly from the population is  $\bar{V}$ . We will argue that the Nash equilibrium of this game is the Wilson pooling equilibrium  $X^W$ . Suppose that firm A chooses the contract  $\hat{X}$  in round 1 and round 2, rather than  $X^W$ . To be profitable, firm 1's offer must lie in the shaded region in figure 8. Since this leaves only type 1 accepting the offer  $X^W$ , the latter is unprofitable and so firm B's best response in round two is to drop its offer. Then all accept the remaining contract  $\hat{X}$ . But  $X^W$  is a zero-profit contract thus  $\hat{X}$  must yield losses. It follows that firm A is strictly better off choosing  $X^W$ .

For the two-type case, it is easy to see that the reactive equilibrium can also be viewed as the equilibrium of a multi-round game. The only difference is that players get an opportunity to make additional offers in the second round, rather than drop offers. Let  $(X_1^R, X_2^R)$  be the reactive (separating) equilibrium. Any profitable deviation  $X$  must pool the two types. Then, in round

2, it is always possible to skim the cream with an additional offer. This leaves the bad workers choosing  $X$  and so the defecting firm ends up with losses.

One difficulty with modifying the rules of the game in this way is that it is hard to know when to stop. A third possibility would be to allow firms to either add or drop offers in the second round. I conjecture that both the Wilson and reactive equilibria are Nash equilibrium of this new game.

More fundamentally, telling a story about a hypothetical adjustment process to justify a static equilibrium is a poor substitute for a formal dynamic model. Spence, in his early work, suggested that if competition were sufficiently fierce, the outcome would most likely be some form of cycle. Recently, theorists have begun analyzing screening using simple evolutionary dynamics. Building on the work of M. Kandoori, George Mailath, and Rafael Rob (1993) and Peyton Young (1993), Georg Noldeke and Larry Samuelson (1997) built a formal evolutionary model for the two-type case. They show that if there is no Nash equilibrium of the Rothschild-Stiglitz one-shot game, the evolutionary dynamical system does not have a stationary point. Instead there is an equilibrium two-period cycle that is stable in the face of low-frequency perturbations. The high-value types always choose the more costly action  $z_H$  while the low types switch back and forth between  $z_H$  and some less costly action  $z_L$ . Suppose that in period  $t$  all workers choose  $z_H$ . Then firms find that the average productivity is  $\bar{V}(z_H)$ . Firms base their offers next period on this period's observations and thus offer a wage  $w_H(t+1) = \bar{V}(z_H)$ . This is sufficiently low that low-quality workers are better off choosing  $z_L$  and receiving a wage  $w_L(t+1) = V_L(z_L)$ . The productivity of workers choosing  $z_H$

then rises to  $V_H(z_H)$ . Firms observing this outcome then offer a wage  $w_H(t+2) = V_H(z_H)$  and the cycle begins again. While this seems to be a potentially promising research program, much work remains to be done. In particular, it will be important to understand the conditions under which equilibria can be readily characterized with more than two types. Moreover, surely the simple adaptive expectations model is too naive. Presumably firms would begin to understand the cycle and thus make wage offers based on the expectation of a continuing cycle.

### 3.3 Signaling

With the informed agents moving first, we have seen that there is a continuum of Nash signaling equilibria. For equilibrium theory, the central question is whether it is possible to place sensible restrictions on beliefs that then support a much smaller set of equilibria. As noted in section 2, it is typical to appeal to the Cho-Kreps intuitive criterion. Unfortunately, while this criterion successfully selects a unique equilibrium in the basic signaling model, it needs to be strengthened to have any bite when the assumptions of the model are relaxed only slightly.

Consider the simple consulting example. As in the basic two-type model, each type has a marginal product that is high or low. A type 1 consultant has a low marginal product and a high cost of signaling, while a type 2 consultant has a high marginal product and a low marginal cost of signaling. There is also a small probability that the consultant is of type 3 or type 4. Type 3 has a marginal cost of signaling slightly lower than type 2 and type 4 has a marginal cost of signaling slightly higher than type 2. Both have a low marginal product. Since types 2, 3, and 4 have very similar signaling costs, we look for an

equilibrium in which they are all treated alike. Let  $\bar{V}_{234}$  be the expected productivity of a consultant of types 2, 3, and 4. Since the conditional probability is high that he is type 2 rather than types 3 or 4,  $V_2 - \bar{V}_{234}$  is small.

Consider the pair of contracts  $(X_1^*, X_{234}^*)$  in figure 9. Since  $X_1^*$  is a best response for type 1 and  $X_{234}^*$  is a best response for the other types, both contracts just break even. Thus  $(X_1^*, X_{234}^*)$  is a Nash equilibrium.

Suppose that the consultant chooses the out-of-equilibrium signal  $\hat{z}$ . As depicted, even if firms were to pay the high marginal product (the contract  $\hat{X}$  in figure 9) type 1 would be worse off choosing  $\hat{z}$  rather than  $z_1^*$ . Thus by the intuitive criterion, only types 2, 3, and 4 could possibly gain. However, the criterion is silent as to what restrictions should be placed on beliefs about the likelihood that it is a type 2 consultant rather than a type 3 or type 4.<sup>15</sup>

The “properness” criterion proposed by Roger Myerson (1978) focuses on the relative advantage to doing so. In a proper equilibrium almost all the weight is placed on the type who gains the most from the defection. Since type 4 has a larger marginal cost than types 2 and 3, properness assigns almost all the weight to type 4. Given such beliefs, it follows that firms would offer a wage too low to be attractive to any type. Then the Nash equilibrium is proper. Indeed any separating Nash equilibrium is proper.

Rather than look directly at payoffs, Jeffrey Banks and Joel Sobel (1987) compare the sets of responses that would make the worker better off. If the set for type 4 is strictly larger than for type 2, Banks and Sobel require that the revised probability that the worker

<sup>15</sup> An almost identical argument holds for signals greater than  $z_{234}$ .

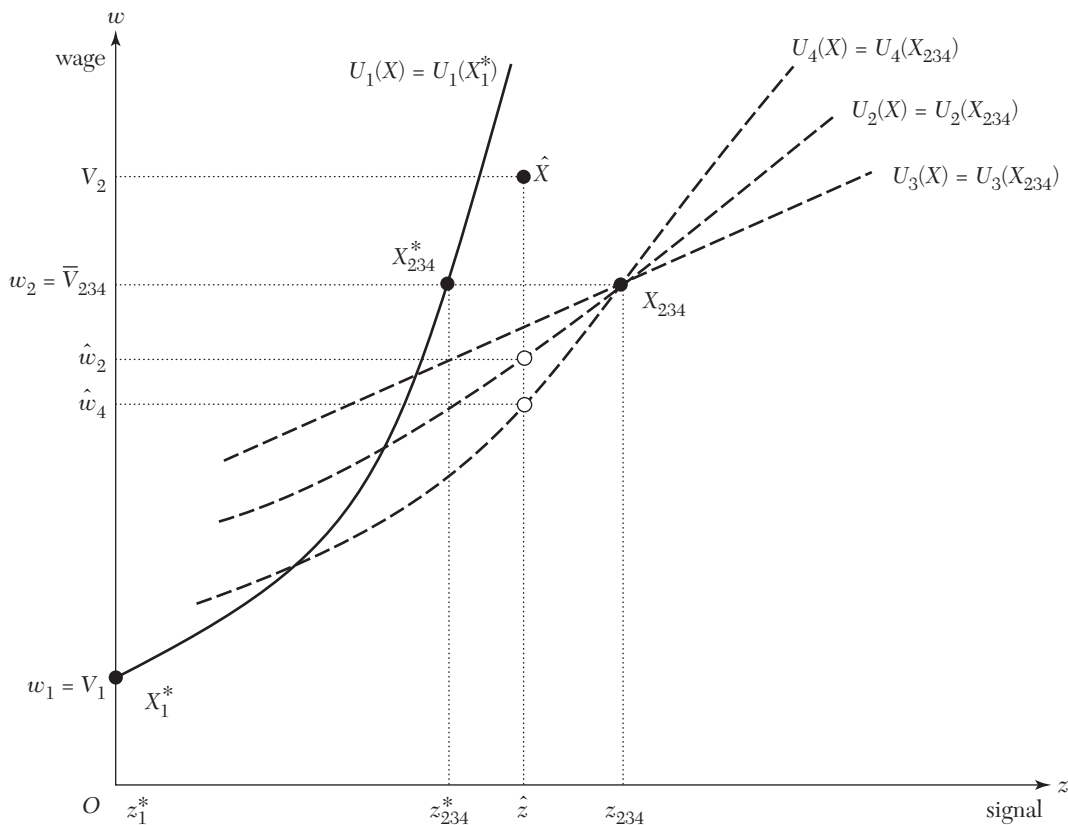


Figure 9. Continuum of Equilibria

is type 4 rather than type 2 should not fall below the prior probability. In this example, all wages above  $\hat{w}_4$  make type 4 better off and all wages above  $\hat{w}_2$  make type 2 better off. Thus the probability placed on type 4 must rise. In particular, the Banks-Sobel criterion does not rule out the belief that it is highly likely that the defector is type 4. With such a belief, the response is a low wage offer. Thus, just as with properness, there is a continuum of Banks-Sobel (or “Divine”) equilibria.

Elon Kohlberg and Jean-Francois Mehtens (1986) propose to restrict the set of Nash equilibria to those that are equilibria of the entire family of games that have the same normal form as the original game. In particular, suppose

that the players can choose either to play the game in round 1 or choose not to play and then play the game in round 2. This modified game is depicted below.

Let the game in the box be the simple consulting example with the four different types (whose preferences are as depicted in figure 9.) Suppose that the Nash equilibrium  $(X_1^*, X_{234})$  is played in the upper box in figure 10. Consider a type who chooses “Don’t Play” in round 1 and then the signal  $\hat{z}$ . Since the high marginal product is  $V_2$ , the most that any firm will offer in response is a wage  $\hat{w} = V_2$ . This is the contract  $\hat{X}$  in figure 9. As depicted, type 1 strictly prefers his Nash equilibrium payoff to this contract. That is, his Nash equilibrium payoff strictly dominates (“Don’t

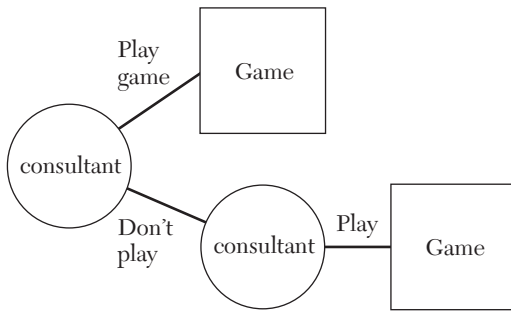


Figure 10. Modified Game with Identical Normal Form

Play,”  $\hat{z}$ . The firm then infers that the signaler is type 2, 3, or 4. However, as with the other qualitative criteria, stability places no restriction on the conditional probability that the signal  $\hat{z}$  was sent by type 2. In particular, we are free to assign a very low conditional probability. Given such beliefs, each firm responds with a wage offer too low to be preferred by any of the types. Then all consultant types are worse off choosing the out-of-equilibrium signal  $\hat{z}$ . It follows that the Nash equilibrium is stable. Indeed all the Nash equilibria that separate type 1 from the other three types are “stable.”

Suppose instead that Bayes’ Rule is used to update beliefs. Then, in response to the deviation to  $\hat{z}$ , the wage offered to types 2, 3, and 4 will be bid up to their expected marginal product  $\bar{V}_{234}$ . If this is the case, types 2–4 indeed have an incentive to deviate. As in the two-type case, only the Pareto dominating equilibrium that separates out type 1 survives.

Of course, as illustrated in section 2, we know that such Grossman-Perry updating of beliefs can lead to nonexistence. The example makes clear how difficult it is to find a refinement of Nash equilibrium that has enough bite to rule out a continuum of equilibria, without also creating an existence prob-

lem. To me, the simplest way out of the maze is to employ the stronger Grossman-Perry approach and then seek conditions that are sufficient to ensure existence.<sup>16</sup> If there is an equilibrium that satisfies the stronger criterion, it is the Pareto dominating separating equilibrium. As I have emphasized, the critical requirement is that, for the signals chosen in this Nash equilibrium, the marginal cost of signaling should decline sufficiently rapidly with type.

#### 4. Industrial Organization

There has been a remarkably rich set of applications of signaling in the industrial organization field. In many cases, papers are not simply straightforward applications, but have advanced the theory significantly. The earliest literature focuses on the role of advertising as a signal of product quality. Phillip Nelson (1974) contrasts advertising of goods that must be consumed before they can be fully appreciated with goods that can be evaluated in the shop. He concludes that advertising of “experience goods” is much more focussed on attracting attention to the brand than providing information about product quality. While he did not attempt a formal model, he argues that high advertising expenditures on brands are seen by consumers as a signal of product quality.

Benjamin Klein and Keith Leffler (1981) and Paul Milgrom and John Roberts (1986) build closely related models of repeat purchasing that yield Nelson’s conjectures. To illustrate the

<sup>16</sup>For a contrary view see Mailath, Masahiro Okuno-Fujiwara, and Andrew Postlewaite (1993), who argue that if an out-of-equilibrium action is observed, the revised beliefs should be fully consistent with some other equilibrium. Positive probability is assigned only to those types who are better off in the alternative equilibrium. The Pareto dominant Nash signaling equilibrium is then the unique “undefeated” equilibrium.

central issues, we will consider a stripped-down version of the Milgrom-Roberts model. Suppose there are two quality levels, high and low. In a world of full information, the firm would sell to one group of customers when it had a high-quality product (at a high price) and another group when its product was of low quality. Each potential customer buys at most one unit per period. Thus, in the high-end market, with demand price function  $p_H(q)$ , the quantity  $q$  is the number of high-end customers. Similarly in the low-end market, if the price is set at  $p_L(q)$ , the quantity  $q$  is the number of low-end customers. Suppose that in period one, buyers do not know quality. However, if advertising is sufficiently intensive, then they will infer that quality is high. After period one, information on advertising is forgotten, but all those who have purchased know product quality. Thus, if and only if quality is indeed high, the firm will maintain its high-end customer base. As a result, there is a payoff to signaling in the short- and long-run for a firm with a high-quality product. A low-quality producer makes a short-run killing if he mimics but must lower his price on all repeat sales after period one, when quality is known.

Let  $r$  be the interest rate and assume an infinite horizon. If the firm is believed to be selling a low-quality product, the present value of its profit stream is the first-period profit plus the discounted future stream of profits  $U_L(q_L) = \Pi_L(q_L) + \frac{1}{r}\Pi_L(q_L)$ , where  $q_L$  is chosen to maximize profit  $R_L(q) - c_Lq$ . If the high-quality firm chooses price  $p_H(q)$  and advertising expenditures  $A$ , which is high enough to signal high quality, the present value of its profit stream is  $U_H(q,A) = \Pi_H(q) - A + \frac{1}{r}\Pi_H(q) = \frac{1+r}{r}\Pi_H(q) - A$ . Given beliefs about the signal conveyed by the advertising, a low-quality firm can fool high-quality cus-

tomers by mimicking in period 1. That is, it can also choose  $A$  and the introductory price  $p_H(q)$ . If it does, it has a present value of

$$\begin{aligned} U_M(q,q_L,A) &= \Pi_M(q) - A + \frac{1}{r}\Pi_L(q_L) \\ &= \Pi_H(q) + (c_H - c_L)q - A + \frac{1}{r}\Pi_L(q_L). \end{aligned} \quad (5)$$

The low-quality firm thus prefers to mimic if, for some  $(q,A)$ ,  $U_M(q,q_L,A) \geq U_L$ . Assuming diminishing marginal revenue, this region must be as depicted in figure 11. Also depicted is an indifference curve  $U_H(q,A) = \hat{U}_H$  for some high-quality firm. Since the present value of the firm is linear in  $A$ , all the high-quality indifference curves are vertically parallel with turning points at the profit maximizing output level  $q_H^*$ . Moreover, from (5), as long as the lower-quality firm has lower costs, it must be the case that  $q_H^* < \bar{q}$ . It follows from the figure that the profit-maximizing separating point is  $(q^s, A^s)$ .<sup>17</sup> Note that the signaling quantity is set lower than the monopoly output under full information. Thus, the introductory price set by the monopoly with a high-quality product is above the full-information monopoly price.

This argument is extended by Birger Wernerfelt (1988), who argues that firms may often be able to signal quality more cheaply by building a reputation for a range of products all benefiting from the "umbrella" reputation of the firm itself. That is, instead of advertising product by product, there are economies of scale in branding a group of products as all belonging to the same part of the quality spectrum.

All these models focus on the opportunity for signaling by a single firm in order to exploit its monopoly power

<sup>17</sup> All points outside the shaded region, which generate a non-negative payoff, are Nash signaling equilibria. Applying the standard refinements yields the unique equilibrium  $S$ .

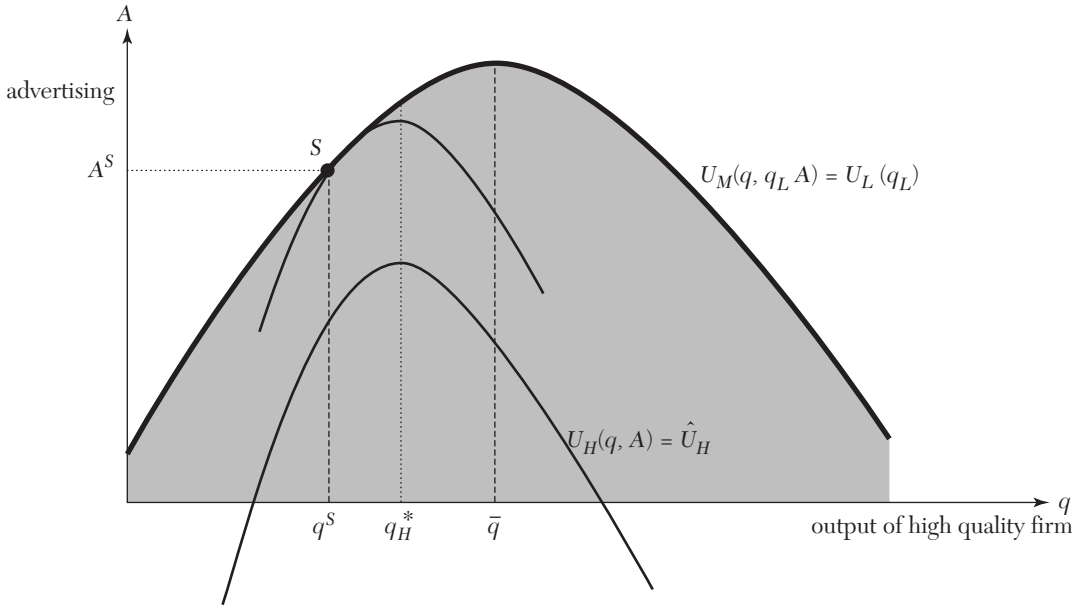


Figure 11. Advertising as a Signal of Product Quality

under imperfect information. Richard Kihlstrom and Michael Riordan (1984) show that if firms are price takers, there can be no such equilibrium with advertising. Firms get zero profits if they are separated, thus it is always advantageous for a low-quality firm to mimic over the initial “experience” period.

A closely related line of research explores conditions under which a high introductory price can alone be a signal of product quality. For this to be the case, there must be some heterogeneity in the ability of consumers to distinguish quality prior to purchase. Kyle Bagwell and Riordan (1991) assume that some consumers have full information while others know only the prior (exogenous) distribution of product quality. Let  $p_H(q)$  be the demand price function when it is believed that quality is high. Let  $c_L$  and  $c_H > c_L$  be the unit costs of a low- and high-quality firm. Then the profit of a firm of quality level  $t$  is  $\Pi_t(q) = p_t(q)(q - c_t), t = L, H$ . We assume that, for each type, marginal

revenue is decreasing so that the profit function is strictly concave with a single turning point at  $q_t^*$ . Then maximized profit is  $\Pi_t^* = p_t(q_t^*)(q_t^* - c_t)$ . If a low-cost firm can trick all consumers into believing it is selling a high-quality product, it faces a demand price  $p_H(q)$  and thus has a profit of

$$\begin{aligned} \Pi_L^m(q) &= p_H(q)(q - c_L) \\ &= \Pi_H(q) + (c_H - c_L)q. \end{aligned} \tag{6}$$

Suppose next that a fraction  $f$  of the consumers are informed and so do not purchase when a low-quality firm mimics the high-quality firm by announcing an introductory price  $p(q)$ . The profit of the mimicking firm is then reduced to  $(1 - f)\Pi_L^m(q)$ . Now it pays to mimic if and only if

$$\Pi_L^m(q) > \frac{\Pi_L^*}{1 - f}. \tag{7}$$

Since the unit cost of production is lower for the mimicking firm,  $\Pi_L^m(q)$  has a unique turning point at  $q^m > q_H^*$ . It

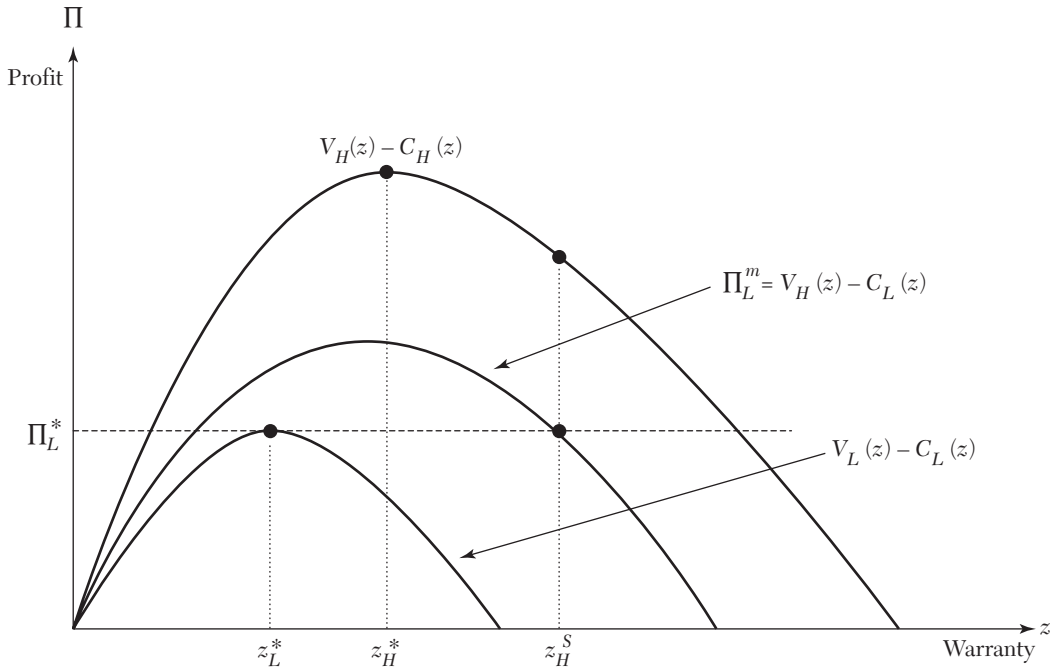


Figure 12. Warranty as a Signal

follows that there is a unique pair of quantities  $q'$  and  $q''$ , where  $q' < q^m < q''$ , such that (7) holds only for quantities in the interval  $q', q''$ .

If the profit-maximizing quantity for the high-quality firm is less than  $q'$ , there is no incentive to mimic. Separation is thus achieved at no cost. On the other hand, if  $q_H^* > q'$ , the least costly separating price is either  $q'$  or  $q''$ . But  $\Pi_L^m(q') = \Pi_L^m(q'')$ . It follows immediately from (6) that  $\Pi_H(q') > \Pi_H(q'')$ . Hence the least costly means of avoiding mimicking is for the high-quality firm to choose the quantity  $q'$ . That is, it sets an introductory price  $p(q') > p(q_H^*)$ .

Another line of research explores the role of warranties as signals of product quality. The earliest papers by Spence (1977a) and Grossman (1981) use many of the ideas from the signaling literature but are really risk-spreading stories. In each case firms sell items of uncertain quality to risk-averse individuals. Firms

are assumed to be risk neutral, thus an efficient contract with buyers involves full coverage.

A simple signaling explanation for warranties is based on product durability (Esther Gal-Or 1989). Suppose that a monopolist provides a warranty that offers to repair any defects until age  $z$ . Let  $V_t(z)$   $t \in \{L, H\}$  be the expected value of the product to consumers if the warranty level is  $z$ . Let  $C_t(z)$  be the expected unit cost of producing the good and providing such a warranty. The expected payoff to a consumer if the monopolist charges a price  $P$  is then  $U_t(z, P) = V_t(z) - P$ . With complete information about the firm's type, the monopoly solution is depicted in figure 12. The firm extracts all of the surplus so that the profit  $\Pi_t(z) = V_t(z) - C_t(z)$  is maximized by setting a warranty level  $z_t^*$  and price  $P_t^* = V_t(z_t^*)$ . But if buyers do not observe quality, a low-quality firm can mimic and charge a price  $P = V_H(z)$ .

The profit of the low-quality firm is then  $\Pi_L^m(z) = V_H(z) - C_L(z)$ . In the figure,  $\Pi_L^m(z_H^*)$  exceeds the full information profit, so mimicking is profitable. The high-quality firm then must increase its warranty level to  $z_H^*$  in order to eliminate the incentive to mimic.

Nancy Lutz (1989) provides an alternative description of signaling in a Spence/Grossman insurance model of warranties. Consumers exhibit moral hazard in taking care of the product, thus insurance coverage is only partial. As in the model above, the costs of providing this partial coverage are higher for a low-quality firm, thus the extent of the warranty is again a potential signal.

Despite the plethora of theories arguing that introductory prices, advertising, and warranties can signal high quality, there is remarkably little applied work seeking empirical support. Moreover, the papers that do attempt to look at the data draw mixed conclusions. Gerstner (1985) examines the relationship between price and quality using data from the Consumers Union *Buying Guide*. Using the *Guide's* quality ranking as a proxy for quality, Gerstner finds only weak support for the hypothesis that higher quality is correlated with higher price. C. Hjorth-Andersen (1991) extends this analysis by introducing a vector of quality indicators and leaving the data to speak for itself on the nature of the overall connection between these indicators and product price. His test is whether there is a positive relationship between the different quality rankings. Using both *Consumer Reports* data and Danish data, he again concludes that there is at best only a weak link between quality and price. He also considers Wernerfelt's argument about umbrella branding and finds only a very weak correlation of quality indicators across different products produced by the same firm. While these results are a

challenge to the theory, it should be noted that neither directly address the point of the theoretical papers which is primarily that firms will seek to signal quality when *introducing* new experience goods.

Joshua Wiener (1985) uses *Consumer Reports* data on automobiles to see whether higher priced cars have better warranties. He finds that indeed there is a strong positive correlation, lending support to the idea that warranties do signal quality. Finally, Daniel Akerberg (1996) presents structural and reduced-form estimates of a dynamic learning model. One of the central questions he asks is whether the effect of advertising a new product primarily signals quality (a "persuasive" effect) or primarily provides information about the product. For the particular product studied (the introduction of a new yogurt) he is unable to find a significant persuasive effect. This paper is a valuable first step in what seems to be a field ripe for detailed empirical investigation, especially as firms begin to seek ways to exploit the vast amounts of sales data stored electronically.

#### 4.1 Limit Pricing

Another area in which signaling models have been central is in the analysis of entry. Consider the case of a monopolist who faces a potential entrant. One important source of informational asymmetry is that each firm is likely to be uncertain about the unit cost of its potential competitor. Given this informational asymmetry, might an incumbent profitably deter entry by setting a "limit price" rather than the monopoly price prior to entry? As Milgrom and Roberts (1982) showed, this may indeed be the case. To illustrate the issues, consider a simple two-period model. In the first period, the incumbent with unit cost  $c_1$  is the only firm in the

market. The entrant, with unit cost  $c_E$ , observes the first-period price and then makes an irrevocable decision whether or not to enter. In period 2, if there is entry, the resulting competition yields a duopoly profit to the incumbent of  $\Pi_1(c_1, c_E)$ . In the absence of entry, the incumbent sets the monopoly price in period 2 and his profit is  $\Pi^*(c_1)$ . In the first period his profit is  $q(p)(p - c_1)$ .

Suppose that the entrant's cost is  $c$  or less with probability  $F_E(c)$ . If all entrants with costs higher than  $c$  are successfully discouraged from entering, the incumbent's profit is

$$U(p, y, c_1) = q(p)(p - c_1) + (1 - F_E(z))\Pi^*(c_1) + \int_0^c \Pi_1(c_1, c_E) dF_E(c_E).$$

The question is whether the incumbent encourages more firms to stay out by setting a lower "limit price" in the first period. Formally, is it possible to characterize a mapping  $c^s(p)$ , from the incumbent's price to the cost of the marginal entrant, such that the lower the equilibrium price, the lower is the cost of the marginal entrant? If this is the case, incumbents will be separated. Thus, the critical entrant has a cost  $c$ , satisfying  $\Pi_E(c_1, c) = 0$ . The pairs  $(c, z)$  satisfying this condition are depicted in the left half of figure 13. Whether or not types are separated hinges on whether an incumbent with a higher cost has a steeper indifference map. That is, for a separating equilibrium, we require that the single-crossing property be satisfied. Mathematically we require that

$$\left. \frac{dc}{dp} \right|_{\bar{U}_1} = - \frac{\frac{\partial U_1}{\partial p}}{\frac{\partial U_1}{\partial c}}$$

increases with the incumbent's cost. While this is not automatically satisfied, it is easy to find cases where the single-

crossing property holds. Therefore "limit pricing" can signal an incumbent's toughness.

One of the points emphasized by Milgrom and Roberts is that in a separating equilibrium the types of firms that do enter are exactly those that would enter if the entrant could directly observe the incumbent's type. Thus, limit pricing does not discourage entry relative to a world of full information. Instead, limit pricing is a mechanism the incumbent uses to discourage entry of those firms that would otherwise enter because of asymmetric information.

One assumption of the Milgrom-Roberts model is that the cost of the potential entrant is uncorrelated with the cost of the incumbent. Joseph Harrington (1986) extends the analysis to the case of correlated costs. Suppose that only after he enters will the entrant know his cost with certainty. If costs are positively correlated, information about the incumbent's cost will affect the entry decision. The incumbent thus has an incentive to signal that his cost is high and thereby discourage entry. Harrington shows that if costs are sufficiently highly correlated, the optimal strategy of the firm is to choose a price higher than the monopoly price, thereby signaling that his cost is high.

In a further follow-up paper, Bagwell and Garey Ramey (1988) consider the further implications if advertising has a direct effect on demand. They show that it is efficient for the incumbent to combine the limit pricing strategy with a second signal—advertising beyond the level that would prevail in the absence of the informational symmetry.

Roberts (1986) offers a model very similar in spirit to explain the "predatory pricing" of an incumbent firm. The informational structure of the model is the same. Here, though, the entrant moves first, choosing whether to enter.

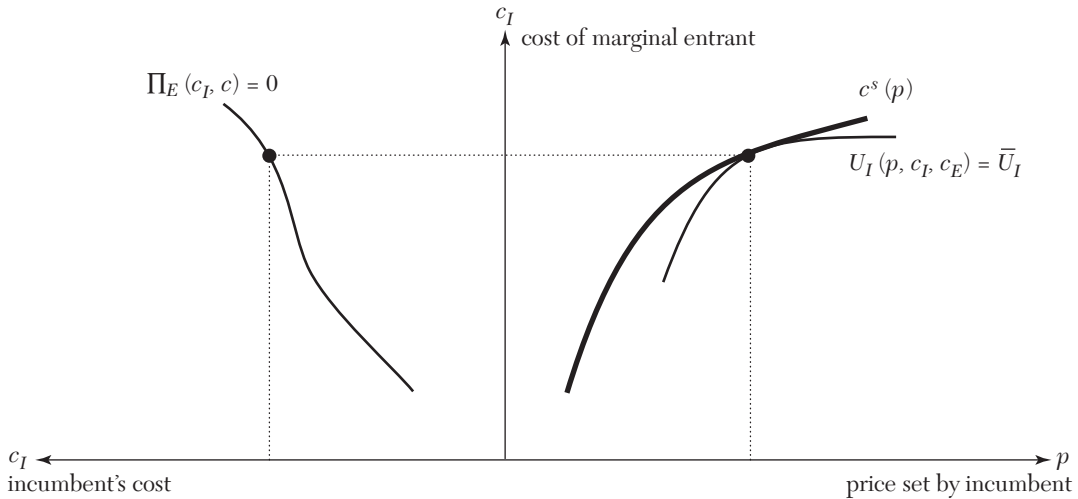


Figure 13. Limit Price Signaling

If it does, the incumbent and entrant compete for one period. The entrant must decide whether to continue or to withdraw and leave the market to the incumbent in period 2. Again it is not too difficult to build a model in which the opportunity cost of flooding the market in the first period (and driving price down) is lower for a tougher incumbent. Thus, the resulting period 1 price is a signal of the incumbent's toughness.<sup>18</sup>

Drew Fudenberg and Jean Tirole (1986) offer an alternative explanation of predation by an incumbent firm. In their model, the entrant is uncertain about how costly it will be to operate in the market. It also does not observe the choice of the incumbent.<sup>19</sup> Let  $s_1$  and  $s_E$

<sup>18</sup> If the incumbent faces an infinite sequence of potential entrants, fairly standard “folk theorem” arguments show that there is an equilibrium in which weaker incumbents mimic the strongest incumbent in responding to entry. As Milgrom and Roberts (1982) and Kreps and Wilson (1982b) show, mimicking remains equilibrium behavior in the initial periods even if there is a long finite horizon.

<sup>19</sup> This could be the quantity sold or the secret discount on the listed price offered to “loyal” customers.

be the strategies of the incumbent and entrant. In the first period, the entrant observes its profit and then uses its own profit  $\Pi_E(s_1, s_E)$  to make an inference about its total cost  $\hat{C} = C(\Pi_E(s_1, s_E), s_E)$ . Since the incumbent's strategy is not observable, his strategy has a direct effect on his own profit and an informational effect on his opponent's inference. This gives the incumbent an incentive to lower price. Note that the entrant is not fooled since he can infer the incumbent's equilibrium strategy. It is simply the non-observability of the strategy that increases the incentive to lower price. Of course, to the extent that the entrant is uncertain about the incumbent's cost, this “signal-jamming” effect and the signaling effect are reinforcing.<sup>20</sup>

LeBlanc (1992) has shown that by adding slightly to the dynamic structure of these games, both limit pricing and predatory pricing can emerge as equilibrium signals. In the initial round the

<sup>20</sup> Kirman and Masson (1986) consider the role of capacity signals as a deterrent of entry. In their paper the entrant is uncertain about the degree to which the incumbent oligopolists operate as a cartel and respond collusively.

limit pricing conveys strength. It is used if the incumbent is very strong and the prior belief is that this is very unlikely. However, if the prior belief is that the incumbent is likely to be strong and the entrant is likely to be weak, then the incumbent would prefer only to signal his strength in the unlikely event that the entry actually takes place. In this situation, there is predatory pricing rather than limit pricing.

While I am not aware of a paper that formally models the capacity decision of the entrant as a signal of strength (low unit cost), it is intuitively clear that such a model could be easily developed along the lines of the limit pricing model. While the timing is different, such a model would seem to flow naturally from the earlier work on equilibrium conjectures by potential entrants. Building such a model would be useful as a part of an evaluation of the relative efficiency of different methods of signaling strength.

One paper, which does focus on capacity signals, provides a rare analysis of entry when the incumbents are members of an oligopoly rather than a monopoly. (This is another area crying out for further study.) William Kirman and Robert Masson (1986) consider a model in which the entrant is uncertain about the degree to which the incumbent oligopolists operate as a cartel and then respond collusively. In the model the weak oligopoly responds with a round of competitive price cuts. Such behavior discourages entry. Thus the collusive oligopoly has an interest in mimicking the weak oligopoly. This it can do by adding enough capacity to simulate the weak oligopoly outcome.

Mailath (1989) does consider simultaneous signaling among oligopolists. His focus is not on deterrence per se, but on the effects of each firm drawing inferences about its opponents' costs. Consider two firms selling a differenti-

ated product. In period 1 neither knows its opponent's cost. Thus a naive choice would be to maximize first-period expected profit. If firm  $B$ 's strategy is to set a price  $p_1^B(c^B)$ , the naive best response of firm  $A$  is to choose  $p_1^A(c^A)$  to solve  $\max_{p_1^A} E_{c^B} \{ \Pi_1^A(p_1^A, p_1^B(\tilde{c}^B), c^A) \}$ . However, the first-period decision will be used by firm  $B$  to draw an inference about firm  $A$ 's actual cost. Assuming that the equilibrium is monotonic, firm  $B$  can invert and infer that  $c^A = c^A(p_1^A)$ . Let  $p_2^B(c^A, c^B)$  be firm  $B$ 's equilibrium price in period 2, given full information. Then if firm  $A$  chooses a first-period price of  $p_1^A$ , its total profit is  $E_{c^B} \{ \Pi_1^A(p_1^A, p_1^B(\tilde{c}^B), c^A) + \Pi_2^A(p_2^A, p_2^B(c^A(p_1^A), \tilde{c}^B), c^A) \}$ . Since the choice of firm  $A$ 's first-period price signals its unit cost, there is an informational effect that the firm must take into account in order to maximize profit. In standard differentiated duopoly models, firm  $B$  responds to a higher cost by raising its price, recognizing that firm  $A$  will also price higher. Thus firm  $A$  has an incentive to push up its first-period price, which induces a higher second-period price for firm  $B$ . In equilibrium, neither firm is fooled. However, the incentive that results from information being signaled leads to higher first-period prices.<sup>21</sup>

Finally, two papers consider the endogenous timing of decisions. Mailath (1993) considers a Cournot game in which the firm with less information about demand moves in period 2. The better-informed firm can choose period 1 or period 3. If it leads, then its choice signals its information to its opponent. Despite this, at least in the model considered, the unique equilibrium satisfying plausible refinements has the informed firm moving first. Andrew Daughety and Jennifer Reinganum

<sup>21</sup> As Mailath notes, there are existence and uniqueness issues that are non-trivial in oligopoly models.

(1994) take this a step further and allow firms to choose whether to acquire information. In equilibrium, a firm knows whether its opponent is informed and thus how much information is conveyed by its future decisions. An agent must then decide whether and when to seek information, knowing that this choice will influence the nature of the signaling game. The game itself is therefore determined endogenously. As in standard signaling models, the intuitive criterion is employed to obtain a unique separating equilibrium in each possible realization of the information acquisition game. In the duopoly production game analyzed in the paper, the two players are *ex ante* identical. For certain parameter values, however, the information acquisition phase of the game has only asymmetric equilibria. Thus, asymmetry is endogenously induced and a signaling game is then played out. The players also choose whether to act simultaneously or sequentially (leader-follower.)

The model is illustrative rather than conclusive. However, issues of timing are important, and making them a part of the solution rather than imposing timing assumptions is another fruitful avenue for further research.

### 5. Labor

As in industrial organization, the basic theory has been used to explain a wide range of theoretical puzzles. However, there is considerably more emphasis on empirical verification. Rather than attempt to cover everything, this section focuses primarily on three areas which have attracted considerable interest. The first series of papers attempts to test Spence's educational screening hypothesis against the traditional human capital explanation of educational choice. The second group examines the implications for promotion when outsiders

(other firms) use this as a signal of information learned on the job by the current employer. The third group of papers looks at labor-management contract issues.

#### 5.1 Educational Screening

Both the human capital model and the screening model imply that earnings should increase with education. Thus simply estimating an earnings function is not likely to shed much light on the screening role of education. Let  $z$  be an individual's educational achievement. Let  $\theta$  be an unobserved variable representing the individual's ability. Suppose an individual of type  $\theta$  and education level  $z$  has a marginal product of  $v = V(\theta, z) + \varepsilon$ , where  $\varepsilon$  is a realization of the independent random variable  $\tilde{\varepsilon}$  which has a zero mean. The cost of achieving education level  $z$  is  $C(\theta, z)$ . In the human capital story, informational problems are of second order. A type  $\theta$  individual chooses  $z^*(\theta)$  to maximize his net payoff  $U(\theta, z, w) = w - C(\theta, z)$ , where  $w = V(\theta, z) + \varepsilon$ . Under weak assumptions, the choice  $z^*(\theta)$  is monotonic. Inverting this, we may write  $\theta = \theta^*(z)$ . He then earns a wage of  $w = V(\theta^*(z), z) + \varepsilon$ . The observed distribution of wages is thus

$$\tilde{w}(z) = V(\theta^*(z), z) + \tilde{\varepsilon}. \quad (8)$$

As discussed in section 2, firms that do not observe marginal product (in the early years on the job) will pay a wage based on educational credentials. A type  $\theta$  individual solves  $\text{Max}_z \{w(z) - C(\theta, z)\}$ . In a screening equilibrium, higher types choose more education. Inverting, there is a monotonic relationship between education and the unobserved ability  $\theta^s(z)$ . Firms bid wages up to expected marginal productivity so that the expected wage is

$$w^s(z) = E\{V(\theta^s(z), z) + \tilde{\varepsilon}\} = V(\theta^s(z), z). \quad (9)$$

Early empirical work (e.g., Paul Taubman and Terence Wales 1973) was

hampered by the absence of an equilibrium model of screening. Since Spence's papers, much of the empirical work starts with the assumption that screening is more important in some sectors than in others. Richard Layard and George Psacharopoulos (1974) compare earnings functions of students who achieve some educational credential (say a bachelor of arts degree) with those who do not. They argue that the credential should have strong explanatory power only in a screening world. For the data that they consider, there is no such strong effect. While, on its face, this is evidence against educational screening, the data is far from ideal. The sample is a set of World War II veterans who were getting a deferred education in a booming job market. Presumably many were "pulled" from education rather than dropped out.

Thomas Hungerford and Gary Solon (1987) use *Current Population Survey* (CPS) data to further test the "sheepskin effect." They find a significant positive effect as implied by screening theory. John Heywood (1994) analyzes additional CPS data and again finds a significant sheepskin effect. However, this effect is significant only in the private non-union sector and not elsewhere. It is far from clear that a screening story can be easily constructed to explain the absence of screening in other sectors.

A serious problem with these studies is that they do not spell out which variant of the traditional human capital model or screening model is to be tested. In the human capital model, the productivity of a college graduate is a function of what he has learned at college. This is positively related to his grades and the quality of the college that he attends. Presumably, those who drop out do so because they find the going tough and their grades are low. Thus, the productivity of the dropouts

is lower than that of a representative individual from the class. When income is regressed against years of college education plus a "sheepskin" dummy, the latter picks up the difference in the rate of capital accumulation among dropouts and the rest of the class. Therefore, if data on dropouts are to be used as evidence, one necessary preliminary step is to provide a theory of why some students drop out.

Of all the empirical work that builds on the theory, the most creative is by Kevin Lang and David Crop (1986). To illustrate their central point, consider the following special case of the screening model described above. The marginal product of a type  $\theta$  individual who achieves an education level  $z$  is  $V(\theta, z) = \theta z$ , while his cost of education is  $C(\theta, z) = \frac{1}{2}z^2/\theta$ . Suppose that every type has the same outside opportunity to earn a wage  $r$  with no college education. With full information, type  $\theta$  is paid a wage equal to his marginal product. He therefore chooses an education level  $z^*(\theta) = \arg\max_z \{\theta z - \frac{1}{2}z^2/\theta\}$ . It is readily confirmed that  $z^*(\theta) = \theta^2$ , and hence that his net payoff is  $U^*(\theta) = \frac{1}{3}\theta^3$ . Since all types can earn  $r$  in another industry, the lowest type,  $\theta_o$ , who enters the industry is just indifferent between doing so and earning  $r$ . Thus  $U^*(\theta_o) = \frac{1}{3}\theta_o^3 = r$  and hence  $\theta_o = (2r)^{\frac{1}{3}}$ . It follows that the minimum education level and wage is

$$(z_o, w_o) = ((2r)^{\frac{2}{3}}, 2r). \quad (10)$$

For all higher types, the wage of type  $\theta$  is  $w^*(\theta) = V(\theta, z^*(\theta)) = \theta^3$ . Then, since  $z^*(\theta) = \theta^2$ , the observed "wage function" is

$$w^*(z) = z^{\frac{3}{2}}, z \geq z_o(r). \quad (11)$$

Next consider a screening equilibrium. From section 2 we know that the outcome is exactly the same for the lowest type who chooses a college education. That is,  $(z_o, w_o)$  satisfies condition (10). Given a wage function  $w(z)$ , each

higher type chooses  $z^s(\theta)$  to solve  $\text{Max}_z\{w(z) - \frac{1}{2}z^2/\theta\}$ . It is readily confirmed that the first-order condition is  $w'(z) = z/\theta$ . In equilibrium, each type has a wage equal to his marginal product, thus  $w = \theta z$ . Combining these two conditions yields the differential equation,  $w(z)w'(z) = z^2$ , with end-point condition (10). Direct integration and substitution yields the screening equilibrium wage function

$$w^2(z) = \frac{2}{3}z^3 + \frac{1}{3}w_o^2, \quad z \geq z_o, \quad z \geq z_o(r), \quad (12)$$

where  $w_o = 2r$ .

The important thing to note is that while a change in the outside opportunity affects the minimum entry level, it does not affect wages for higher types in the full-information world. However, in the screening equilibrium, the entire wage function rises with an increase in the outside wage. The intuition is relatively straightforward. With the improved outside opportunity, the minimum type to enter college is greater than before. Therefore, the necessity for a type to signal that he is better than all lower types in the market is reduced. As a result, over-investment in education falls and everyone is made better off. This can only be achieved by a rise in the equilibrium wage function.

Effectively, the same argument applies when the mandated minimum educational credential is increased. Lang and Crop look at the effects of changes in compulsory attendance laws. They conclude that there is a significant "ripple effect" as predicted by the screening model.

Another approach, which builds on the theory, begins with the observation that screening will be most important in those sectors where productivity is relatively hard to measure. In Riley (1979a) the key assumption is that the different sectors are not segregated according to

ability. Then a subset of types must be indifferent between working in the "screened" and "unscreened" sectors. The only way this can occur is if, when holding ability constant, jobs in the unscreened sector involve less education. In addition, holding education constant, wages in the unscreened sector are higher. This observation is then used to separate jobs (as classified in the *CPS* data) into an "unscreened" group with low education and above-average wages and a second "screened" group with high education and below-average wages. The test of the screening hypothesis is whether there are other differences between the two groups, which can be predicted by screening theory.

One crucial issue for potential testing is how quickly firms begin to identify true productivity and subsequently adjust wages to reflect this new information. In jobs where screening is important, one would expect the earnings function to explain wages very well early in the life cycle. In the extreme case, represented by the wage function in equation (9), education and wage are perfectly correlated in the screened sector, whereas the correlation is weaker in the unscreened sector (see equation 8).

If, in addition, firms accumulate information about true productivity over the early years in the work force, the explanatory power of education should decline. Thus the ratio of unexplained residuals for the screened group over that for the "unscreened" group should rise over time. Riley observes such an effect.

Kenneth Wolpin (1981) also takes the two-sector approach using the NBER-Thorndike data first used by Taubman and Wales (1973) and then by Layard and Pscharopoulos (1974). All the men in this sample were given extensive ability tests. If these tests are unbiased

estimates of true ability, one can then compare the education levels of the two groups to see whether ability is lower for dropouts. Wolpin finds only small ability differences and therefore concludes that the data provide little support for screening theory. However, as already noted, traditional human capital theory yields precisely the same prediction.

Eric Friedland and Roger Little (1981) use *National Longitudinal Survey* data to explore the difference between the self-employed and salaried workers. At least in this sample, the self-employed have higher average educational achievement and incomes than salaried workers. The inference is that this group is a high-ability group and thus the tests that appeal to overlapping ability levels no longer apply. This suggests that new theoretical predictions are necessary before the self-employed can be used in tests for screening.

Finally, Wim Groot and Hessel Oosterbeek (1994) use Dutch longitudinal data to see what happens to students who either skip a year of school or are held back and forced to repeat a year. Screening theory would surely expect the former to be a positive and the latter a negative signal. Since these effects are not observed in the data, the authors conclude that this is strong evidence against the screening hypothesis. Ideally one would like wage data early in the life cycle. However, in the data examined, there is a thirty-year gap between the early collection of school data and wage data. Thus the absence of a significant effect may be simply due to overwhelming noise. Still, this does seem a fruitful avenue for further empirical investigation.

One criticism of the educational screening hypothesis is that if the main role of (say) graduating with a higher GPA from UCLA is to convey informa-

tion about natural ability, there is no reason for firms to wait until graduation. Firms can look instead at lower division grades and recruit from the freshman class! However, once students understand that the cost of signaling is only the cost of getting high grades for a couple of quarters, the signaling equilibrium collapses.<sup>22</sup>

Noldeke and Eric van Damme (1990) examine this informal argument in a simple two-type model. Their key innovation is the assumption that the labor market is open continuously. Suppose one firm does start recruiting from the freshman class. As they note, it is a best response of other firms to immediately follow the leader. If this response is sufficiently rapid, there is no reason for a student to accept the first offer because, by waiting a very short interval, he will get a better offer. The “instantaneous reaction” thus sustains the standard equilibrium. Noldeke and van Damme then consider a discrete time version of the model and show that there is a unique equilibrium. In the limit, as the time between offers gets smaller, the equilibrium approaches the “instantaneous reaction” equilibrium.

The problem with such an argument is that instantaneous responses greatly reduce incentives to innovate. In reality, much of the incentive for change comes from the inability of potential competitors to react immediately. Thus, it seems to me that the Weiss critique cannot be so easily overcome. What one would really like is a model in which education is not simply a credential but also adds to human capital. A more complete model of the educational process would surely also allow colleges to choose how to bundle courses into concentrations (degrees). In this case, much of the value of the education may lie in

<sup>22</sup> See Andrew Weiss (1983).

such concentrations. Then dropping out early might be very costly.

### 5.2 *Employment Status as a Signal*

As workers gain experience on the job, their employers gather information about them. This information will typically be better than information available to outsiders. The employer can therefore hold down wage increases and so earn rents from above-average quality workers. However, if it becomes necessary to promote high-quality experienced workers into higher level jobs, the promotion becomes a signal to outsiders.

In the first paper to explore this issue, Michael Waldman (1984) assumes that workers accumulate firm-specific human capital on the job. With full information, an individual is switched from job A to job B (“promoted”) if his marginal product is higher in job B. Consider a worker of type  $\theta$  whose productivity is the same in the two jobs. With full information, firms would be indifferent as to whether or not to promote. With asymmetric information, outsiders bid up the wages of those promoted to the average productivity of this group. Thus the type  $\theta$  worker has a productivity below the equilibrium wage in job B. Hence he will not be promoted. It follows that asymmetric information results in fewer workers being promoted. In a second paper (Waldman 1990), it is assumed that workers accumulate general human capital. Then, if an individual is promoted, outside firms have an incentive to expend resources to obtain a noisy estimate of the employee’s actual productivity. The promoted worker gets a small initial wage increase and then outsiders compete for his services in an auction. Again this has the effect of raising the quality of individuals promoted above that which would prevail with full information.

Dan Bernhardt and David Scoones (1993) extend this argument, noting that the current employer can discourage the investment in information-gathering by offering an especially outstanding worker a preemptive wage. The wage is credible if it is sufficiently high to be unprofitable unless offered only to those very close to the top of the ability distribution. As long as the support of these abilities is sufficiently small, it is not profitable for outsiders to incur the cost of pre-auction information gathering.

The authors find informal confirming evidence in academic job markets, where promotion to tenure is a strong positive signal of quality. Even though many candidates fail to get tenure, initial salary increases of those achieving tenure are typically in the modest to moderate range. Salaries several years after promotion are then determined by the strength of the auction. Less commonly, exceptional faculty are given large raises with tenure, thus discouraging the opening of an auction.<sup>23</sup>

A closely related paper by Milgrom and Sharon Oster (1987) contrasts the promotion of different skill levels when part of the population is “visible” (ability is recognized) and part is invisible (ability known only to the current employer). In contrast to Waldman, a key underlying assumption is that the market observes the actual ability of anyone who is promoted. Again the question is who among the insiders, if anyone, will be promoted. It is shown that the higher rents earned on unpromoted insiders leads to promotion of intermediate quality workers rather than the most able.

Similar arguments have been made about the implications of the decision

<sup>23</sup> While I certainly know of universities where this story has a ring of truth, it really would be helpful to have some serious empirical investigation of the phenomenon.

to lay off workers. Robert Gibbons and Lawrence Katz (1991) note that with asymmetric information, termination is a negative signal of worker quality when the terminating firm is a viable operation. This is not true if the entire firm is closing down. They then look at data from the *Displaced Worker Supplements* to the *Current Population Survey* and find strong supporting evidence. Finally, Ching-to Ma and Weiss (1993) use a signaling argument to explain the length of unemployment spells. In their model, a laid-off worker who accepts a poor job is sending a sufficiently negative signal about his productivity that relatively more able workers choose to be unemployed.

### 5.3 Bargaining

The equilibrium theory of bargaining between two agents initiated by Ariel Rubinstein (1982) has been fruitfully applied to union management negotiations. In the basic noncooperative bargaining model, the two parties make alternative offers. Suppose the two parties are bargaining over whether the profits of  $V$  should be retained by the firm or distributed to the workers as wages. The critical idea is that if the agent making the first offer (agent 1) looks ahead to the next time he makes an offer, he can reason as follows: If my equilibrium payoff is  $U_1$  and if I get to make an offer two periods from now, I should be able to use my equilibrium strategy from then on and get at least  $U_1$  at that time. Discounting back one period, my opponent will realize that in period 2, when he makes his first counteroffer, I can command a discounted payoff of  $\delta U_1$ . Then the best he can do is ask for the remaining surplus  $U_2 = V - \delta U_1$ . A symmetric argument for agent 2 establishes that  $U_1 = V - \delta U_2$ . Combining these two results, the

equilibrium payoffs (discounted to the time of each agent's first offer) are  $U_1 = U_2 = \frac{V}{1+\delta}$ . Finally, discounting agent 2's first offer to the first period, the equilibrium payoffs are  $(U_1, U_2) = \left(\frac{V}{1+\delta}, \frac{\delta V}{1+\delta}\right)$ . Note that the total gains to the two parties sum to  $V$ . This can only be the case if there is no time cost through delay. Thus the equilibrium strategy is for agent 1 to ask for a fraction  $\frac{1}{1+\delta}$  of the total pie and for agent 2 to accept this immediately.

Explanations for the delays observed in bargaining typically introduce a central role for sorting. Suppose that the firm has private information about the profit level. In the "screening" version,<sup>24</sup> the union starts with high offers, knowing that if profits are high, the cost of delay is high and so the firm will be willing to accede. Each round that the firm refuses the union's offer, the union revises downwards its beliefs about the profits of the firm. Suppose that in round  $t$  beliefs about the future round imply an expected wage bill (discounted to period  $t + 1$ ) of  $w_{t+1}$ . Given these beliefs, the firm will accept any wage offer  $w_t$  satisfying  $V - w_t \geq \delta(V - w_{t+1})$ . Rearranging, the firm will accept a wage satisfying the constraint

$$w_t \leq (1 - \delta)V + \delta w_{t+1}. \quad (13)$$

This inequality is depicted in figure 14 for valuations of  $V_H$ ,  $V_M$ , and  $V_L$ . If there is sorting, then by period 3, it is a common belief that the firm's profit level is  $V_L$ . Appealing to Rubinstein's result, there is a unique equilibrium wage offer  $w_3(V_L)$ . Now consider a firm with profit  $V_M$ . Given this period 3 wage, the firm will accept any period 2 wage satisfying (13). Thus the best period 2 offer by the workers is  $w_2(V_M)$  where the constraint is just satisfied. The first period wage offer is similarly computed. Whether or not

<sup>24</sup> See, for example Grossman and Perry (1986a), and Sobel and Ichiro Takahashi (1983).

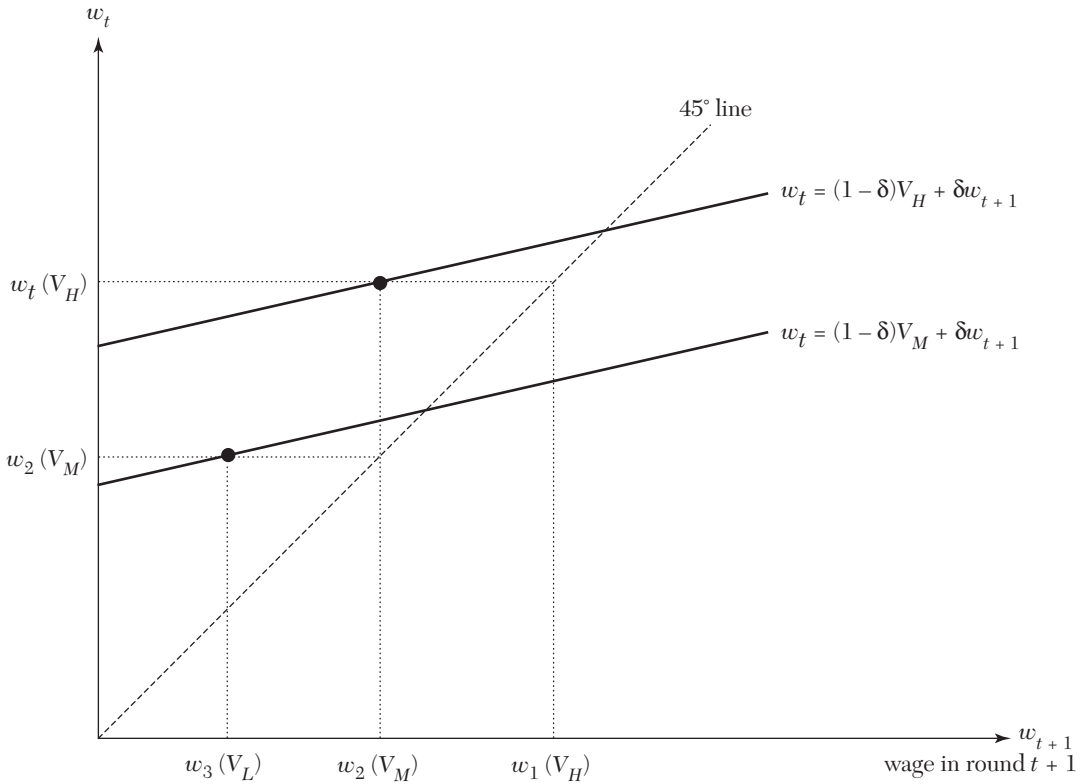


Figure 14. Equilibrium Sorting Offers

full sorting of the three types is optimal depends upon the difference between the profit levels and the likelihood of each. For example, if  $V_M$  and  $V_L$  are sufficiently close, it is more profitable to simply separate out a high-profit firm. One theoretical difficulty with this model is that it does not explain the delay if the time between rounds is small. Indeed, as Faruk Gull, Hugo Sonnenschein, and Wilson (1986) show, in the limit, as the time between bargaining rounds goes to zero, there is no delay.<sup>25</sup>

The signaling version of the model by

<sup>25</sup> At least this is the case under their stationarity assumption. As Lawrence Ausubel and Raymond Deneckere (1989) have since shown, delay is possible under weaker assumptions. It should also be noted that the screening argument rests heavily on the assumption of a fixed order of offers and counteroffers.

Anat Admati and Perry (1987) also has alternating offers, but each agent can choose how long to wait before presenting his offer. Suppose that the union makes the first offer. Again, the fact that a more profitable firm loses more by delaying allows for separation. Suppose that the firm has either a high-profit  $V_H$  or a low-profit  $V_L$ . If the firm does not delay its counter-offer, the union believes that the profit is high. Appealing to Rubinstein's theorem, the union (the agent making the first move) will then accept a wage equal to  $w(0) = \frac{1}{1+\delta}V_H$ . If in fact the profit is low, the firm delays until time  $z$  before presenting its counteroffer. If this delay is an effective signal, the union then believes that the profit is low. As the responder to the offer, the Rubinstein

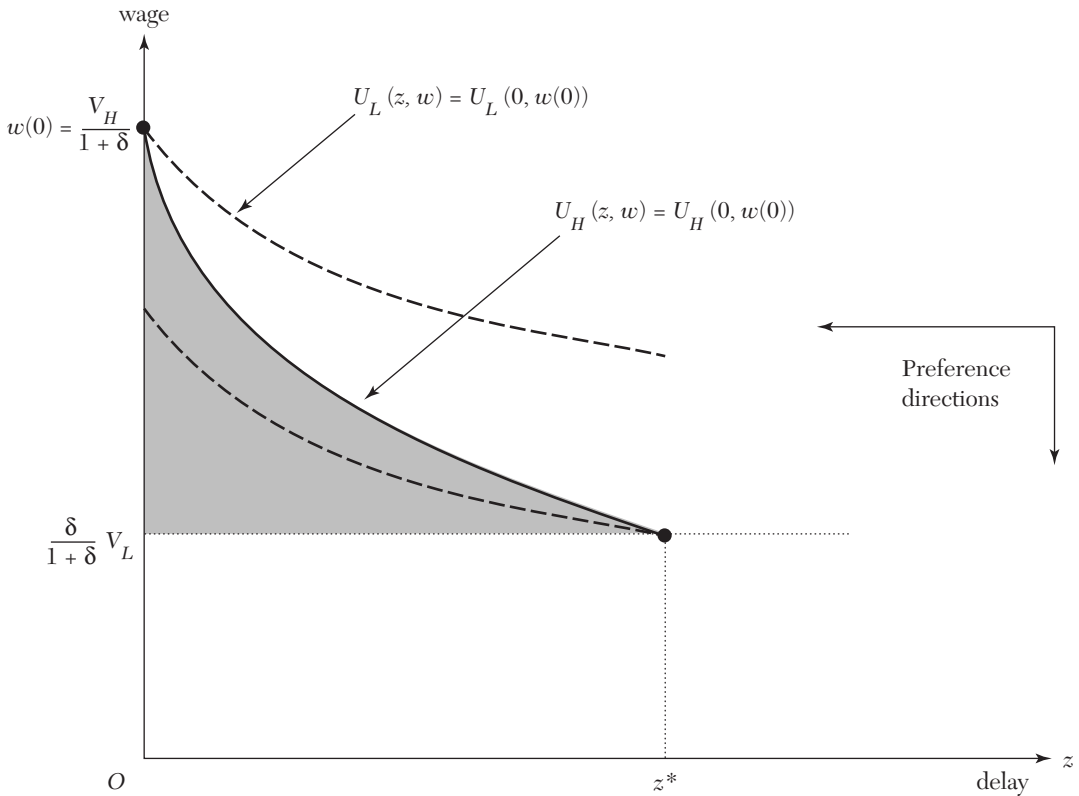


Figure 15. Signaling Equilibrium

equilibrium yields the union a wage equal to  $w(z) = \frac{\delta}{1+\delta}V_L$ . The payoff to the firm if the wage  $w$  is accepted at time  $z$  is  $U_H(z, w) = \delta^z(V_H - w)$ . The indifference curve for a high-profit firm through  $(0, w(0))$  is depicted in figure 15. The high-profit firm strictly prefers any offer in the interior of the shaded region to  $(0, w(0))$ . Also depicted are the flatter (dashed) indifference curves of a low-profit firm with payoff function  $U_L(z, w) = \delta^z(V_L - w)$ . Thus if the profit is low, the firm's cost minimizing separating strategy is to delay its counteroffer until time  $z^*$ .<sup>26</sup>

A third model of bargaining delay is

<sup>26</sup> It should be noted that the result relies heavily on the assumption that the union must wait for the firm to counter its original offer, rather than revise its own offer.

the “war of attrition” where each party tries to wait the other out. Suppose that the settlement will be  $w$  if it is the union that concedes and  $\bar{w} > \underline{w}$  if the firm concedes. Let the firm's assessment of the probability that the union will concede by time  $t$  be  $p(t)$ . Then if time  $t$  is reached, the conditional probability that the union will concede in the time-interval  $dt$  is  $\frac{dp}{1-p(t)}$ . Then the discounted expected payoff from conceding at time  $t + dt$  is  $(V - \underline{w})\frac{dp}{1-p} + (V - \bar{w})(1 - \frac{dp}{1-p})e^{-rdt}$ . If the firm concedes at  $t$  it has a payoff of  $V - \bar{w}$ . Collecting terms, the expected net gain to waiting the extra time interval is  $dU = (V - \underline{w})\frac{dp}{1-p} + (V - \bar{w})rdt = \frac{V - \underline{w}}{V - \bar{w}} [(V - \bar{w})\frac{dp}{1-p} - rdt]$ . Note that the term in square brackets is increasing in  $\hat{V}$ . Thus if a firm with profit level  $\hat{V}$  is better off

waiting until  $t + dt$ , rather than conceding at  $t$ , all firms with higher profit levels are also. It follows that the equilibrium strategies are separating with the firms with higher profits staying in the competition longer.

There is a considerable body of empirical evidence on the duration of strikes and the terms of the settlement.<sup>27</sup> In a thought-provoking paper, John Kennan and Wilson (1989) review the data and the implications of the three theories. They conclude that the signaling models fare rather poorly when confronted with the evidence. On the other hand, they argue that both the attrition model<sup>28</sup> and the screening model are able to explain “many of the salient features of the data.”

## 6. Finance

Finance has not only a fascinating array of applications of screening and signaling theory, but also an impressive set of investigations into their empirical significance. As with the other fields, the literature is vast, and I will focus on some key issues rather than attempt to be comprehensive. The traditional finance literature assumes that any information that owners and managers (“insiders”) have about future firm performance is known to current and prospective shareholders (“outsiders”). From this follows the famous Miller-Modigliani Irrelevance Theorem. In such a world, changes in capital structure, dividend increases, etc. have no effect on the value of a firm’s assets. In reality,

<sup>27</sup> See Sheena McConnell (1989) and the references therein.

<sup>28</sup> Kennan and Wilson consider only the simplest attrition model in which there is no informational asymmetry. Adding asymmetry (as discussed here) should help to distinguish the attrition from the screening models, for in the former it is the high-profit firms that continue to hold out, while low-profit firms settle early. In the latter it is the high-profit firms that concede more quickly.

however, there are systematic price effects of announcements by firms. The signaling literature argues that these announcements convey inside information to the marketplace.

### 6.1 Adverse Selection

One of the early highly influential papers is Stewart Myers and Nicholas Majluf’s (1984) discussion of adverse selection when raising cash to fund a new project. Consider a group of firms, all of which appear similar to outsider investors but differ in their true value; that is, firms of lower-than-average value are overpriced by the market. Then equity-holding insiders of low-value firms will be eager to finance a new project through a new issue of equity. On the other hand, any sufficiently undervalued firm will be worse off financing through a new offering of equity. The market is thus subject to adverse selection.

Consider the following simple variant of the Myers-Majluf model. Only the owners of a firm (the “insiders”) know the true value of a firm  $V(t)$ , where  $V'(t) > 0$  and  $t \in [\alpha, \beta]$ . Since it will be helpful later, we also define the average value of all firms whose type is no greater than  $t$ ,  $\bar{V}(t) = E\{V(\tilde{t}) \mid \tilde{t} \leq t\}$ . A new project requires an injection of funds  $C$  and has a payoff with present value  $B > C$ . Let  $P$  be the market value of the firm after the new equity issue. The new shareholders, who provide  $C$  in new funds, then have a total shareholding of  $\frac{C}{P}$ . Current shareholders of a firm with a prior true value of  $V(t)$  thus end up with a payoff of  $U(t, P) = (1 - \frac{C}{P})(B + V(t))$ . In a world of full information, the current market value is equal to the present value of the firm, that is,  $P = B + V(t)$ . Substituting into the above expression,  $U(t, P(t)) = B - C + V(t)$ . Thus, the insiders capture all the gains from the new issue.

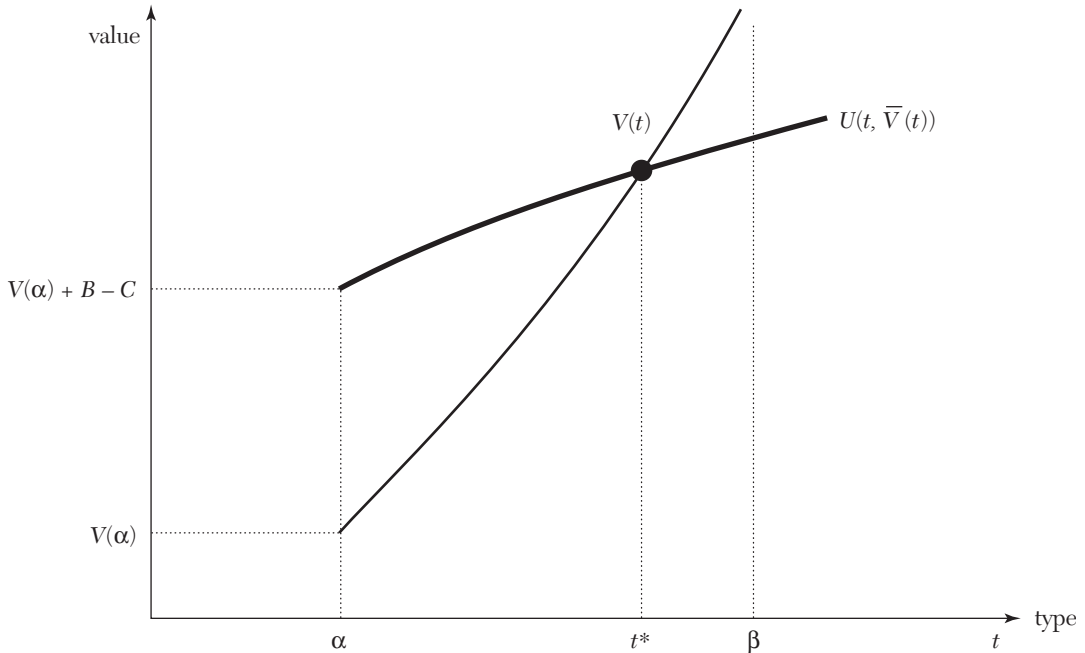


Figure 16. Financial Market Equilibrium

With informational asymmetry, suppose that outsiders believe that only those types of firms  $s \in [\alpha, t]$  will enter the market for new equity. Then the expected value of the post-issue firm will be  $B + \bar{V}(t)$ . Given such beliefs, outsiders will bid up the price of the firm to this expected value. Then the value to insiders becomes  $U(t, \bar{V}(t)) = (1 - \frac{c}{\bar{V}(t)})(B + V(t))$ . It is easily confirmed that  $U(\alpha, \bar{V}(\alpha)) = V(\alpha) + B - C > V(\alpha)$ . Moreover, unless the net value of the project is large,  $U(\beta, \bar{V}(\beta)) < V(\beta)$ . Thus, as depicted in figure 16, the two curves must intersect at some  $t^*$ . In equilibrium, the marginal firm type  $t^*$  is just indifferent between investing and not investing in the new project. All higher types are strictly worse off investing.

### 6.2 Capital Structure

One large set of papers considers how the firm's capital structure might signal about otherwise unobservable

earnings. Two early papers use standard signaling arguments. Hayne Leland and David Pyle (1977) point out that if insiders are risk averse, it is costly to commit to holding a sizeable fraction of their portfolios in the firm, rather than be fully diversified. However, the marginal cost of holding more shares is higher for insiders who have a low-quality firm. Thus, the single-crossing property holds. Stephen Ross (1977) introduces a bonus (or penalty) scheme for the manager based on the firm's future price relative to the face value of the debt issued. The marginal cost of issuing additional debt is lower for a higher quality firm since the probability of paying the penalty is lower.

### 6.3 Non-dissipative Signals

Most of the literature on capital structure abstracts from issues of risk and managerial incentives and focuses instead on the financing of new investment.

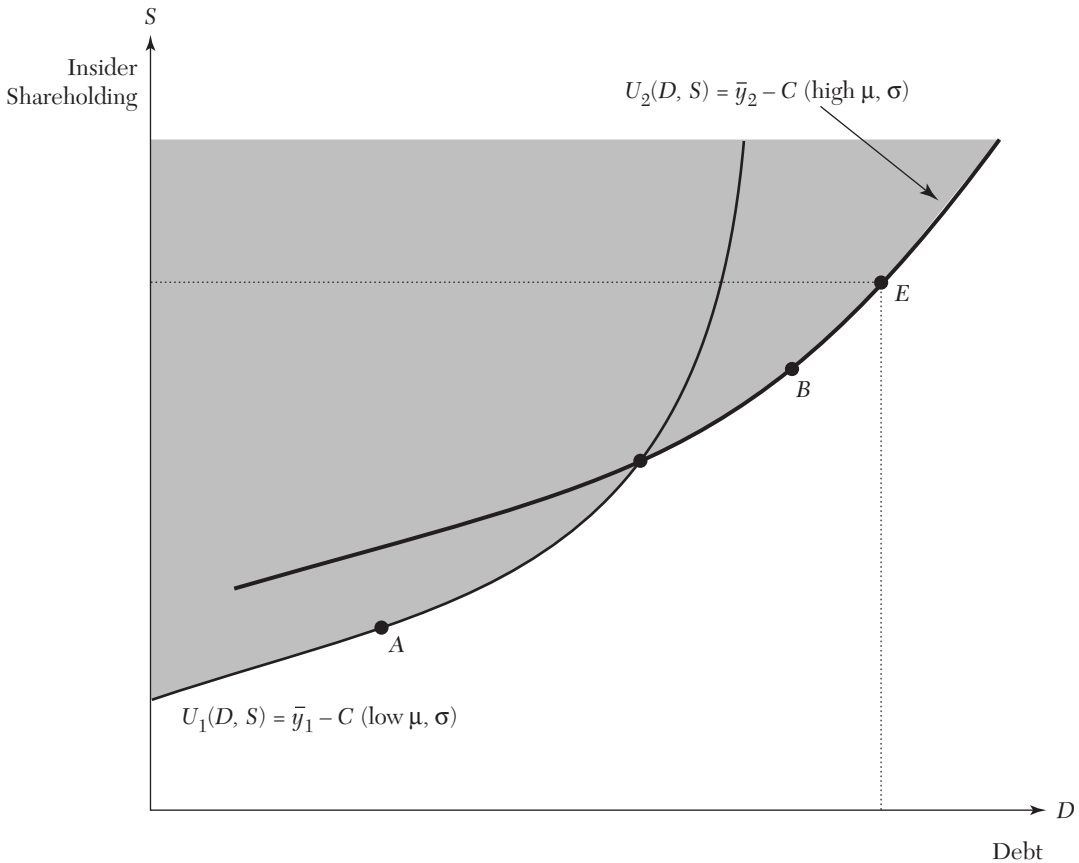


Figure 17. Efficient Separating Equilibrium

Suppose firm  $i$  with  $i = 1,2$  needs to raise  $C$  in order to finance its investment plan. This plan will yield earnings  $\tilde{y}_i$ . Initially we will assume that outsiders have full information. For simplicity, we assume that the interest rate is zero so that outsiders demand a return of  $C$  and so the net expected payoff to insiders is  $\bar{U}_i = \bar{y}_i - C$ . The investment is to be financed by a combination of risky debt and equity. We define  $D$  to be the face value of the debt and  $S$  to be the final equity share of the current owners. The insiders thus get a fraction  $S$  of any income in excess of the debt, that is,  $U_i(D,S) = SE\{Max\{\tilde{y}_i - D, 0\}\} = \bar{U}_i = \bar{y}_i - C$ . In the case of pure equity financing, this reduces to  $U_i(0,S) = S\bar{y}_i = \bar{U}_i = \bar{y}_i - C$ . Thus,

if firm 2 has a higher expected return, the insiders retain a higher equity share.

Next consider a pure debt financing. The expected return to the debt-holders is  $U_i(D,1) = E\{Max\{\tilde{y}_i - D, 0\}\} = \bar{U}_i = \bar{y}_i - C$ . Suppose, following Robert Heinkel (1982), that the firm with the higher mean return is also considerably more risky. Then the face value of the pure debt issue will be higher for firm 2. Given these assumptions, indifference curves for the two firms are as depicted in figure 17.

Consider any pair of capital structures  $A$  and  $B$ , one to the left and one to the right of the intersection point, along the lower envelope of the two indifference curves. Firm 1 strictly

prefers to finance at *A* and firm 2 at *B*. Thus the high-mean/high-variance firm separates by issuing a sufficiently large amount of debt. In contrast to the basic signaling model in which there is overinvestment in the signaling activity (relative to a world of full information), here signaling is efficient. Of course, firms are not limited to the simple debt equity choice illustrated here. As Michael Brennan and Alan Kraus (1987) show, any financial instruments with the property that the outer envelope of the efficient indifference curves has a segment for each type of firm can be used to induce efficient separation. For related papers applying this principle, see Gunther Franke (1987), Thomas Noe (1989), M. P. Narayaman (1988), George Constantinides and Bruce Grundy (1990), and Gautam Goswami, Noe, and Michael Rebelló (1995).

Efficient separation requires more extreme asset structures if firms' earnings distributions can be ordered according to conditional first-order stochastic dominance. Suppose that for any pair of realizations  $y'$  and  $y'' > y'$ ,  $\text{Prob}\{\tilde{y}_2 > y'' \mid \tilde{y}_2 > y'\} > \text{Prob}\{\tilde{y}_1 > y'' \mid \tilde{y}_1 > y'\}$ . Thus, firm 2 has more probability weight at the upper tail of the distribution. Given this assumption, it can be shown that the intersection point of the two indifference curves lies to the northeast of the point *E*, where  $S = 1$ . Thus efficient separation requires that the high-quality firm choose  $S > 1$ , that is, issue debt and retire equity.

The empirical literature on price effects of new issues and repurchase finds considerable support for the idea that announcements convey inside information to outsiders, that is, support for signaling theory. Theo Vermaelen (1981) examines the effect of stock repurchases on prices. He shows that there is a significant price effect and that this is a predictor of favorable post-

announcement abnormal returns. Deborah Lucas and Robert McDonald (1990) show that firms typically float a new issue after an unusual run-up in stock price and that the announcement of the new issue depresses the price. On the other hand, Michael Barclay and Clifford Smith (1995) argue that the variation of the priority structure of corporate liabilities across firms is much better explained by incentive-contracting arguments than signaling.

#### 6.4 *Dividends as Signals*

Another puzzle for finance theory is why firms offer dividends even though they are double-taxed. Sudipto Bhattacharya (1979) and Kose John and Joseph Williams (1985) argue that taxable dividends signal firm quality. Following John and Williams, suppose firms need to raise a fixed amount of capital to fund operations. This is funded through the sale of equity. The higher the firm's current price, the greater will be the insider's share of the final output. The firm with a higher expected final output then gains more from holding a higher final share. Thus, a higher quality firm is willing to accept a smaller increase in firm value in return for accumulating greater tax liabilities (a higher dividend.)

Morton Miller and Kevin Rock (1985) generalize the model and introduce the scale of investment as a choice. Let  $y_i$  be first period earnings (known only to insiders.) An amount  $z$  is distributed as a dividend and the remainder  $I = y_i - z$  is invested. Given an investment of  $I$ , the firm can produce an expected second period output of  $Q(I)$ . Assuming (for simplicity) that the interest rate is zero, the present expected value of the firm is  $V_i(z) = y_i - z + Q(I) = z + Q(y_i - z)$ . Miller and Rock assume that the manager's objective is to maximize a weighted average of the current and

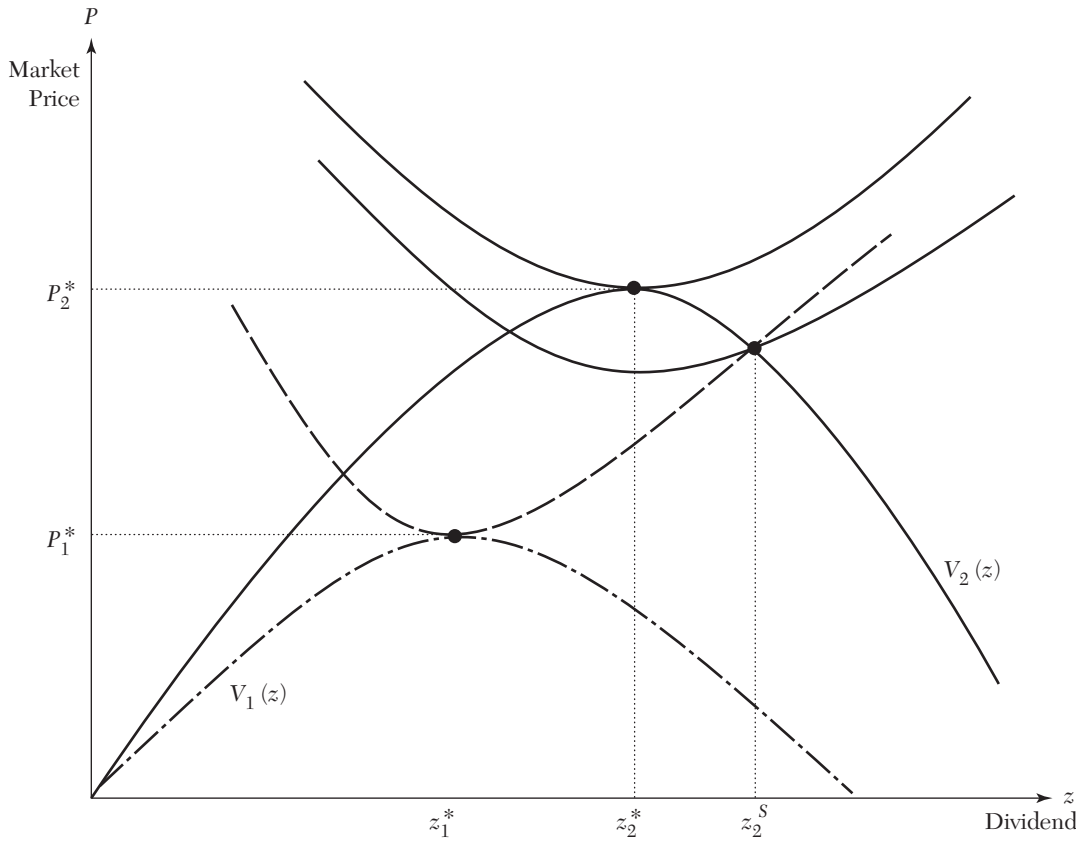


Figure 18. Dividend Signaling

future value of the firm,  $U_i(z, P) = \alpha P + \beta V_i(z)$ . With full information, the equilibrium price is the present value. Thus, the firm's objective is to solve  $\text{Max}_z \{U_i(z, P) \mid P = V_i(z)\}$ . The solution for the low- and high-earnings firms are depicted in figure 18 above. With full information, the value of each firm is maximized so the equilibrium dividend is where the curve  $V_i(z)$  takes on its maximum. Note that  $(z_2^*, P_2^*)$ , the dividend-price pair for the high-earnings firm, is strictly preferred by the low-earnings firm over its full information outcome. Thus, the high-quality firm must increase its dividend to  $z_2^S$  in order to separate itself.

Generalizing this argument, Rama-

sastry Ambarish, John, and Williams (1987) and Williams (1988) allow a firm to relax its budget constraint by issuing new equity to finance the investment. Thus the new equity can act as a signal instead of the dividend. Even when dividends are taxed, they show that the least costly signal is a combination of a new issue and dividend. While there is plenty of evidence that dividend changes result in changes in the market value of the asset, the appropriate test is to see whether the announcement is followed by "surprising" post-dividend returns. Empirical research (see, for example, N. J. Gonedes 1978; Larry Lang and Robert Litzenberger 1989; and Aharon Ofer and D. Siegel 1987) is at

best weak. Thus, the dividend puzzle remains.

### 6.5 *Convertible Debt*

Suppose a firm has convertible debt and the market value of stock reaches the call price. While standard arguments suggest that it is in the firm's interest to convert immediately, it is quite common for firms to wait. Milton Harris and Artur Raviv (1985) offer a signaling explanation. Suppose that when the call becomes feasible the firm has private information that earnings will be down. Then the firm will be overvalued and there is no reason to delay. On the other hand, if the insiders believe that good news will be forthcoming, the firm is undervalued. It is then more profitable to delay and thus reduce dilution of ownership. The immediate conversion of the debt then conveys bad news to the market and the price of the firm should drop. For those who delay conversion, the same story continues to hold. Suppose that, given its private information, a firm is just indifferent between converting and waiting  $t$  periods after the bond conversion can be forced. Then with more favorable private information, this firm has an incentive to wait longer. Thus for delayed conversions the price effect should still be negative.

Ofer and Ashok Natarajan (1987) look at post-conversion returns and find that they decline, as predicted by the signaling model. Sankarshan Acharya (1988) directly tests the Harris and Raviv model by comparing firms that force immediately with those that choose to delay. Again the data conforms well to the signaling explanation for delay.

### 6.6 *Initial Public Offerings*

When firms initially go public, it is typical for the underwriter to set the price

so that the issue is oversubscribed.<sup>29</sup> As Roger Ibbotsen (1975) first showed, the resulting underpricing is large. One explanation for this effect is the winner's curse (Rock 1986). Suppose that bidders can be divided into those that are informed and those that are not. The former will not bid on the relatively poor issues so the uninformed have to be compensated with a low asking price in order for an issue to be fully subscribed.

The largest informational asymmetry, however, seems likely to be between the current owner and potential buyers. Ivo Welch (1989) argues that firms will underprice to signal quality if they expect to go back into the market later to issue additional equity. The higher the initial underpricing, the more optimistic the firm is about its growth prospects (and the need for additional equity). On the other side of the market, the signal of a deeper price discount means that buyers are willing to pay more for the second issue.

Welch's one-parameter model is generalized by Franklin Allen and Gerald Faulhaber (1989) to allow for information about the project to emerge over time. Mark Grinblatt and Chuan Yang Hwang (1989) generalize the model to allow for uncertainty about multiple unobservable characteristics. In the latter paper both the mean and variance of a firm's return are unobservable. The two characteristics are signaled by the firm's choice of a price discount at the IPO and the fraction of the equity retained by the insiders.

The signaling story is then tested by Narasimhan Jegadeesh, Mark Weinstein, and Welch (1993). While they find the evidence consistent with the signaling story, they also show that

<sup>29</sup> A recent listing in Hong Kong of a company doing business in mainland China was 100 times oversubscribed!

returns in the six weeks after the listing also effectively signal both a higher probability of returning to the market and a larger seasoned issue. Thus, there is apparently no special role associated with the under-pricing itself. Instead, the data is broadly consistent with the view that the market is better informed than the seller and the underwriter and that IPO under-pricing is simply an underestimate of value by the seller.

### 7. *Other Fields*

While space precludes a complete discussion of applications in other fields, two groups of papers deserve particular mention. Both are on the interface of economics and politics. The first group of papers focuses on political competition. Banks (1990a) models campaign platforms as signals of candidates' behavior if elected. The platforms convey information about future actions, since the greater the deviation from them, the more likely a politician is to incur the electorate's wrath at the end of his term. A multi-period model with similar implications is developed by Harrington (1993). Banks (1990b) also considers a voting game in which the political authority has private information about the implications if the current proposals are not voted through. The way the agenda is set then signals the private information of the political authority. Charles Cameron and Peter Rosendorff (1993) ask how congressional committees with agency oversight authority are able to affect an agency's plans when the committee has no authority to overrule decisions. They argue that the decision to hold a formal hearing (costly to all parties) should be viewed as an equilibrium signal that the committee majority is resolute. As an immediate implication, the agency's equilibrium response is typically to offer conces-

sions to lower the cost of the hearing. As a final example Susanne Lohmann (1993) offers an argument on why voting can be rational despite the extreme unlikelihood of being the swing voter. In the signaling equilibrium, leaders use the size of the majority on (say) a referendum as a cue for political action. Then each vote has an impact, and with the low cost of going to the polls (or mailing in), the net benefits from voting are positive.

The second group of papers uses signaling theory to better understand the extent to which an announcement about government policy is credible. The most-cited early papers are by Robert Barro and David Gordon (1983) and David Backus and John Driffil (1985a,b), which focus on monetary policy and inflation. Other influential contributions are Vickers (1986), Alex Cukierman, and Allan Meltzer (1986), and Kenneth Rogoff and Anne Siebert (1988).

Dani Rodrik (1998) extends the analysis of credibility of government to issues in trade and financial liberalization. A government serious about reform can get better aid terms if it can signal its seriousness and so distinguish itself from would-be mimickers that are simply seeking foreign aid. This is accomplished by undertaking prior "painful" trade reform. Since the mimicking government places a lower value on the long-run benefits of the reform, the early trade reform becomes an equilibrium signal as long as the proposed aid flow is not too large. A related paper by Rogoff (1990) offers an equilibrium model of the business cycle. The political budget cycle (from one election to the next) is part of a process of multi-dimensional signaling. Multiple signals are also featured in a paper by Torsten Persson and Sweder Wijnbergen (1993) that explores the use of wage-price

controls to mitigate the credibility problem. It is shown that a stabilization program combining a restrictive monetary policy with wage price controls is less costly (more efficient) than one using monetary policy as the only signal.

Last but definitely not least, three empirical studies attempt to seek evidence that governments do signal credibility. Allan Drazen and Paul Masson (1994) use inter-country interest rate differentials as a reflection of the market's estimate of the probability of devaluation. They argue that under the signaling hypothesis an announcement of a continuing "tough" monetary policy, in the presence of continuing unemployment, will raise the probability of a future devaluation, thus leading to a widening spread. The data on adjustments to the European exchange rate mechanism appear to be broadly consistent with this prediction. Masson (1995) draws similar conclusions from British data prior to the devaluation of the British pound in 1992. Finally, Karen Lewis (1995) asks whether intervention in foreign exchange markets by the United States can be understood as a signal of a toughening stance by the Federal reserve. If so, such interventions should have been followed by credit tightening. For the period analyzed (1985–90), the data is broadly consistent with signaling, but the evidence is far from overwhelming.

### 8. *Final Remarks*

In this essay, my primary goal has been to show that a remarkable collection of new economic insights has emerged from the twin theories of screening and signaling. In all three of the primary areas of application, there are now clear explanations of a wide range of economic phenomena, where formerly there were just puzzles. My

second goal has been to emphasize testing of the theory and to suggest that further development of the theory will make this easier. Theoretical models are often of the bare-bones type, where the objective is to demonstrate that information asymmetry and self-selection provides a logically consistent explanation for some observed behavior. Richer models, with somewhat more microeconomic detail, will provide a foundation for both estimation and calibration. Once fitted to the data, it will be possible to determine whether the equilibrium costs of screening and signaling are small or large relative to the benefits. If the cost-benefit ratio is high, there is a strong incentive for the market to seek alternative means of information transmission. It is likely that in environments where this is the case, there will be evidence of direct testing, early monitoring, etc.—all provided to greatly reduce, if not eliminate, asymmetric information.

As I look to the future, my hope is that in the applied fields, there will be more effort to derive theoretical foundations for testing the theory, particularly in the field of industrial organization. Since, in the signaling story, good news is conveyed to the market by some action, this should be reflected in the market valuation of the firm. Thus for any publicly traded firm, one should observe stock price effects of signaling. In labor economics, the connection between the theory and testing has often been rather loose. With more careful attention to the underlying model, new implications may lead to new tests. In particular, productivity changes in other sectors have quite different implications for the wage-education profile than a traditional human capital wage profile. The connection between the theory and data has been explored most fully in the field of finance. While quite a number

of papers report data findings consistent with the theory, others find the evidence to be less than compelling. In some cases contributors to the applied theory have even undertaken their own empirical tests of the theory and found it wanting. This is a sign of a healthy field.

While the underlying theory may seem well settled, much work remains. I have emphasized the need for further discussion of equilibrium in which screening/signaling costs are not perfectly negatively correlated with quality. Assuming consensus can be reached for such models, we will have a stronger foundation for equilibrium in the current models in which the negative correlation is perfect. Models of imperfect signals will also offer additional opportunities for empirical analysis. When separation of types is incomplete, continuing information-gathering is likely to be important.<sup>30</sup>

## REFERENCES

- Acharya, Sankarshan. 1988. "A Generalized Econometric Model and Tests of a Signaling Hypothesis with Two Discrete Signals," *J. Finance* 53:2, pp. 413–29.
- Akerberg, Daniel. 1996. "Advertising, Learning, and Consumer Choice in Experienced Good Markets: An Empirical Examination," mimeo, Yale U.
- Admati, Anat R. and Motty Perry. 1987. "Strategic Delay in Bargaining," *Rev. Econ. Stud.* 54:3, pp. 345–64.
- Akerlof, George A. 1970. "The Market for 'Lemons': Qualitative Uncertainty and the Market Mechanism," *Quart. J. Econ.* 84:3, pp. 488–500.
- Allen, Franklin and Gerald R. Faulhaber. 1989. "Signaling by Underpricing in the IPO Market," *J. Finan. Econ.* 23:2, pp. 303–23.
- Ambarish, Ramasastry; Kose John and Joseph Williams. 1987. "Efficient Signaling with Dividends and Investments," *J. Finance* 92:2, pp. 321–43.
- Ausubel, Lawrence M. and Raymond J. Deneckere. 1989. "Reputation in Bargaining and Durable Goods Monopoly," *Econometrica* 57:3, pp. 511–31.
- Backus, David and John Driffill. 1985. "Inflation and Reputation," *Amer. Econ. Rev.* 75:3, pp. 530–38.
- Bagwell, Kyle and Garey Ramey. 1988. "Advertising and Limit Pricing," *Rand J. Econ.* 19:1, pp. 59–71.
- Bagwell, Kyle and Michael H. Riordan. 1991. "High and Declining Prices Signal Product Quality," *Amer. Econ. Rev.* 81:1, 224–39.
- Banks, Jeffrey S. 1990a. "A Model of Electoral Competition with Incomplete Information," *J. Econ. Theory* 50:2, pp. 309–25.
- . 1990b. "Monopoly Agenda Control and Asymmetric Information," *Quart. J. Econ.* 104:2, pp. 445–64.
- Banks, Jeffrey S. and Joel Sobel. 1987. "Equilibrium Selection in Signaling Games," *Econometrica* 55:3, pp. 647–61.
- Barclay, Michael J. and Clifford W. Smith Jr. 1995. "The Priority Structure of Corporate Liabilities," *J. Finance* 50:3, pp. 899–917.
- Barro, Robert J. and David B. Gordon. 1983. "Rules, Discretion and Reputation in a Model of Monetary Policy," *J. Monetary Econ.* 12:1, pp. 101–21.
- Bernhardt, Dan and David Scoones. 1993. "Promotion, Turnover, and Preemptive Wage Offers," *Amer. Econ. Rev.* 83:4, pp. 771–90.
- Bhattacharya, Sudipto. 1979. "Imperfect Information, Dividend Policy and 'The Bird in the Hand' Fallacy," *Bell J. Econ.* 9:1, pp. 259–70.
- Brennan, Michael and Alan Kraus. 1987. "Efficient Financing under Asymmetric Information," *J. Finance* 42:5, pp. 1225–43.
- Cameron, Charles M. and Peter B. Rosendorff. 1993. "A Signaling Theory of Congressional Oversight," *Games Econ. Behavior* 5:1, pp. 44–70.
- Cho, In-Koo and David M. Kreps. 1987. "Signaling Games and Stable Equilibria," *Quart. J. Econ.* 102:2, pp. 179–221.
- Cho, In-Koo and Joel Sobel. 1990. "Strategic Stability and Uniqueness in Signaling Games," *J. Econ. Theory* 50:2, pp. 381–413.
- Constantinides, George M. and Bruce D. Grundy. 1990. "Optimal Investment with Stock Repurchase and Financing as Signals," *Rev. Finan. Stud.* 2:4, pp. 445–65.
- Cukierman, Alex and Allan H. Meltzer. 1986. "A Theory of Ambiguity, Credibility, and Inflation under Discretion and Asymmetric Information," *Econometrica* 54:5, pp. 1099–128.
- Daughety, Andrew F. and Jennifer F. Reinganum. 1994. "Asymmetric Information Acquisition and Behavior in Role Choice Models: An Endogenously Generated Signaling Model," *Int. Econ. Rev.* 35:4, pp. 795–819.
- Drazen, Allan and Paul R. Masson. 1994. "Credibility of Policies versus Credibility of Policymakers," *Quart. J. Econ.* 109:3, pp. 735–54.
- Franke, Gunther. 1987. "Costless Signaling in Financial Markets," *J. Finance* 42:4, pp. 809–22.
- Friedland, J. Eric and Roger D. Little. 1981. "Self-Employed Workers: Returns to Education and Training," *Econ. Ed. Rev.* 1:3, pp. 315–37.

<sup>30</sup> For example, in the automobile insurance industry, a driver's record, rather than the degree of co-insurance each driver accepts, seems to be the primary determinant of insurance premiums.

- Fudenberg, Drew and Jean Tirole. 1986. "A 'Signal-jamming' Theory of Predation," *Rand J. Econ.* 17:3, pp. 366-76.
- Gal-Or, Esther. 1989. "Warranties as a Signal of Quality," *Canadian J. Econ.* 22:1, pp. 50-61.
- Gerstner, Eitan. 1985. "Do Higher Prices Signal Higher Quality?" *J. Marketing Res.* 22:2, pp. 209-15.
- Gibbons, Robert and Lawrence F. Katz. 1991. "Layoffs and Lemons," *J. Lab. Econ.* 9:4, pp. 351-81.
- Gonedes, N.J. 1978. "Corporate Signaling, External Accounting and Capital Market Equilibrium: Evidence on Dividends, Income and Extraordinary Items," *J. Acc. Res.* 16:1, pp. 26-79.
- Goswami, Gautam; Thomas Noe, and Michael Rebbello. 1995. "Debt Financing under Asymmetric Information," *J. Finance* 50:2, pp. 633-59.
- Grinblatt, Mark and Chuan Yang Hwang. 1989. "Signaling and the Pricing of New Issues," *J. Finance* 44:2, pp. 393-420.
- Groot, Wim and Oosterbeek, Hessel. 1994. "Earnings Effects of Different Components of Schooling: Human Capital versus Screening," *Rev. Econ. Statist.* 76:2, pp. 317-21.
- Grossman, Sanford J. 1981. "The Informational Role of Warranties and Private Disclosure about Product Quality," *J. Law Econ.* 24:3, pp. 461-83.
- Grossman, Sanford and Motty Perry. 1986a. "Sequential Bargaining under Asymmetric Information," *J. Econ. Theory* 39:1, pp. 120-54.
- . 1986b. "Perfect Sequential Equilibrium," *J. Econ. Theory* 39:1, pp. 97-119.
- Gull, Faruk; Hugo Sonnenschein, and Robert Wilson. 1986. "Foundations of Dynamic Monopoly and the Coase Conjecture," *J. Econ. Theory* 39:1 pp. 155-90.
- Harrington, Joseph E. Jr. 1986. "Limit Pricing When the Potential Entrant Is Uncertain," *Econometrica* 54:2, pp. 429-37.
- . 1993. "The Impact of Reelection Pressures on the Fulfillment of Campaign Promises," *Games Econ. Behav.* 5:1, pp. 71-97.
- Harris, Milton and Artur Raviv. 1985. "A Sequential Signaling Model of Convertible Debt Call Policy," *J. Finance* 40:5, pp. 1263-81.
- . 1991. "The Theory of Capital Structure," *J. Finance*, 46:1, pp. 297-355.
- Heinkel, Robert. 1982. "A Theory of Capital Structure Relevance under Imperfect Information," *J. Finance* 37:5, pp. 1141-50.
- Hellwig, Martin. 1987. "Some Recent Developments in the Theory of Competition in Markets with Adverse Selection," *Europ. Econ. Rev.* 31:1-2, pp. 319-25.
- Heywood, John S. 1994. "How Widespread are Sheepskin Returns to Education in the U.S.?" *Econ. Ed. Rev.* 13:3, pp. 227-34.
- Hjorth-Andersen, C. 1991. "Quality Indicators in Theory and in Fact," *Europ. Econ. Rev.* 35:8, pp. 1491-505.
- Hungerford, Thomas and Gary Solon. 1987. "Sheepskin Effects in the Returns to Education," *Rev. Econ. Statist.* 69:1, pp. 175-77.
- Ibbotson, Roger G. 1975. "Price Performance of Common Stock New Issues," *J. Finan. Econ.* 2:3, pp. 235-72.
- Jegadeesh, Narasimhan; Mark Weinstein and Ivo Welch. 1993. "An Empirical Investigation of IPO Returns and Subsequent Equity Offerings," *J. Finan. Econ.* 34:2, pp. 153-75.
- John, Kose and Joseph Williams. 1985. "Dividends, Dilution, and Taxes: A Signaling Equilibrium," *J. Finance* 40:4, pp. 1053-69.
- Kandoori, M.; George J. Mailath, and Rafael Rob. 1993. "Learning, Mutation and Long Run Equilibria in Games," *Econometrica* 61:1, pp. 29-56.
- Kennan, John and Robert Wilson. 1989. "Strategic Bargaining Models and Interpretation of Strike Data," *J. Appl. Econometrics* 4:sup. pp. s87-s130.
- Kihlstrom, Richard E. and Michael H. Riordan. 1984. "Advertising as a Signal," *J. Polit. Econ.* 92:3, pp. 427-50.
- Kirman, William I. and Robert T. Masson. 1986. "Capacity Signals and Entry Deterrence," *Int. J. Ind. Org.* 4:1, pp. 25-42.
- Klein, Benjamin and Keith B. Leffler. 1981. "The Role of Market Forces in assuring Contractual Performance," *J. Polit. Econ.* 89:4, pp. 615-41.
- Klitgaard, Robert. 1991. *Adjusting to Reality*. San Francisco: ICS Press.
- Kohlberg, Elon and Jean-Francois Mertens. 1986. "On the Strategic Stability of Equilibria," *Econometrica* 54:5, pp. 1003-38.
- Kreps, David and Robert Wilson. 1982a. "Sequential Equilibria," *Econometrica* 50:4, pp. 863-94.
- . 1982b. "Reputation and Imperfect Information," *J. Econ. Theory* 27:2, pp. 253-79.
- Lang, Kevin and David Kropp. 1986. "Human Capital versus Sorting: The Effects of Compulsory Attendance Laws," *Quart. J. Econ.* 101:3, pp. 609-24.
- Lang, Larry H. P. and Robert H. Litztenberger. 1989. "Dividend Announcements. Cash Flow Signaling vs. Free Cash Flow Hypothesis?" *J. Finan. Econ.* 24:1, pp. 181-91.
- Layard, Richard and George Psacharopoulos. 1974. "The Screening Hypothesis and the Returns to Education," *J. Polit. Econ.* 82:5, pp. 985-99.
- LeBlanc, Greg. 1992. "Signaling Strength: Limit Pricing and Predatory Pricing," *Rand J. Econ.* 23:4, pp. 493-506.
- Leland, Hayne E. and David H. Pyle. 1977. "Informational Asymmetries, Financial Structure, and Financial Intermediation," *J. Finance* 32:2, pp. 371-87.
- Lewis, Karen K. 1995. "Are Foreign Exchange Intervention and Monetary Policy Related, and Does It Really Matter?" *J. Bus.* 68:2, pp. 185-214.
- Lohmann, Susanne. 1993. "A Signaling Model of Informative and Manipulative Political Action," *Amer. Polit. Sci. Rev.* 87:2, pp. 319-33.
- Lucas, Deborah J. and Robert McDonald. 1990.

- "Equity Issues and Stock Price Dynamics," *J. Finance* 45:4, pp. 1019-43.
- Lutz, Nancy A. 1989. "Warranties as Signals under Consumer Moral Hazard" *Rand J. Econ.* 20:2, pp. 239-55.
- Ma, Ching-to Albert and Andrew M. Weiss. 1993. "A Signaling Theory of Unemployment," *Europ. Econ. Rev.* 37:1, pp. 135-57.
- Mailath, George J. 1989. "Simultaneous Signaling in an Oligopoly Model," *Quart. J. Econ.* 104:2, pp. 417-27.
- . 1993. "Endogenous Sequencing of Firm Decisions," *J. Econ. Theory* 59:1, 169-82.
- Mailath, George J.; Masahiro Okuno-Fujiwara, and Andrew Postlewaite. 1993. "Belief-Based Refinements in Signalling Games," *J. Econ. Theory* 60:2, pp. 241-76.
- Masson, Paul R. 1995. "Gaining and Losing ERM Credibility: The Case of the United Kingdom," *Econ. J.* 105:2, pp. 571-82.
- McConnell, Sheena. 1989 "Strikes, Wages and Private Information," *Amer. Econ. Rev.* 79:4, pp. 801-15.
- Milgrom, Paul and Sharon Oster. 1987. "Job Discrimination, Market Forces, and the Invisibility Hypothesis," *Quart. J. Econ.* 102:3, pp. 453-476.
- Milgrom, Paul and John Roberts. 1986. "Price and Advertising Signals of Product Quality," *J. Polit. Econ.* 94:4, pp. 796-821.
- . 1982. "Limit Pricing and Entry under Incomplete Information: An Equilibrium Analysis," *Econometrica* 50:2, pp. 443-59.
- Miller, Merton H. and Kevin Rock. 1985. "Dividend Policy under Asymmetric Information," *J. Finance* 40:4, pp. 1031-51.
- Mirrlees, James. 1971. "An Exploration in the Theory of Optimum Income Taxation," *Rev. Econ. Stud.* 38:2, pp. 175-208.
- Myers, Stewart C. and Nicholas Majluf. 1984. "Corporate Financing and Investment Decisions when Firms Have Information that Investors Do Not Have," *J. Finan. Econ.* 13:2, pp. 187-221.
- Myerson, Roger. 1978. "Refinement of the Nash Equilibrium Concept," *Int. J. Game Theory* 7:1, pp. 73-80
- Narayanan, M. P. 1988. "Debt versus Equity under Asymmetric Information," *J. Finan. Quant. Anal.* 23:1, pp. 39-51.
- Nelson, Phillip. 1974. "Advertising as Information," *J. Polit. Econ.* 82:4, pp. 729-54.
- Noe, Thomas H. 1989. "Capital Structure and Signaling Game Equilibria," *Rev. Finan. Stud.* 1:4, pp. 331-55.
- Noldeke, Georg and Larry Samuelson (1997), "A Dynamic Model of Equilibrium Selection in Signaling Markets," *J. Econ. Theory* 73:1, pp. 118-56.
- Noldeke, Georg and Eric Van Damme. 1990. "Signalling in a Dynamic Labour Market," *Rev. Econ. Stud.* 57:1, pp. 1-23.
- Ofer, Aharon R. and Ashok Natarajan. 1987. "Convertible Call Policies: an Empirical Analysis of an Information-Signaling Hypothesis," *J. Finan. Econ.* 19:1, pp. 91-108.
- Ofer, Aharon. R. and Siegel Daniel. 1987. "Corporate Financial Policy, Information and Market Expectations: An Empirical Investigation of Dividends," *J. Finance* 42:4, pp. 889-911.
- Persson, Torsten and Sweder van Wijnbergen. 1993. "Signaling, Wage Controls and Monetary Disinflation Policy," *Econ. J.* 103:1, pp. 79-97.
- Riley, John G. 1975. "Competitive Signalling," *J. Econ. Theory* 10:2, pp. 174-86.
- . 1979a. "Testing the Educational Screening Hypothesis," *J. Polit. Econ.* 87:5, s227-s252.
- . 1979b. "Informational Equilibrium," *Econometrica*, 47:2, pp. 331-59.
- . 1985. "Competition with Hidden Knowledge," *J. Polit. Econ.* 93:5, pp. 958-76.
- Roberts, John. 1986. "A Signaling Model of Predatory Pricing," *Oxford Econ. Pap.* 38:1, pp. 75-93.
- Rock, Kevin. 1986. "Why New Issues Are Underpriced," *J. Finan. Econ.* 15:1-2, pp. 187-212.
- Rodrik, Dani. 1998. "Promises, Promises: Credible Policy Reform Via Signaling," *Econ. J.* 99:3, pp. 756-72.
- Rogoff, Kenneth. 1990. "Equilibrium Political Budget Cycles," *Amer. Econ. Rev.* 80:1, pp. 21-36.
- Rogoff, Kenneth and Anne Siebert. 1988. "Elections and Macroeconomic Policy Cycles," *Rev. Econ. Stud.* 55:1, pp. 1-16.
- Ross, Stephen A. 1977. "The Determination of Financial Structure," *Bell J. Econ.* 8:1, pp. 23-40.
- Rothschild, Michael and Joseph E. Stiglitz. 1976. "Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information," *Quart. J. Econ.* 90:4, pp. 629-49.
- Rubinstein Ariel. 1982. "Perfect Equilibrium in a Bargaining Model," *Econometrica*, 50:1, pp. 97-110.
- Sobel, Joel and Ichiro Takehashi. 1983. "A Multistage Model of Bargaining," *Rev. Econ. Stud.* 50:3, pp. 411-26.
- Spence, A. Michael. 1977a. "Consumer Misperceptions, Product Failure and Producer Liability," *Rev. Econ. Stud.* 44:3, pp. 561-72.
- . 1977b. "Entry, Capacity, Investment and Oligopoly Pricing," *Bell J. Econ.* 10:1, pp. 1-19.
- . 1973. "Job Market Signaling," *Quart. J. Econ.* 87:3, pp. 355-79.
- Taubman, Paul J. and Terence J. Wales. 1973. "Higher Education, Mental Ability, and Screening," *J. Polit. Econ.* 81:1, pp. 28-55.
- Vermaelen, Theo. 1981. "Common Stock Repurchases and Market Signaling: An Empirical Analysis," *J. Finan. Econ.* 9:2, pp. 139-83.
- Vickers, John. 1986. "Signaling in a Model of Monetary Policy with Incomplete Information," *Oxford Econ. Pap.* 38:3, pp. 443-55.
- Vickrey William. 1961. "Counterspeculation, Auctions and Competitive Sealed Tenders," *J. Finance* 16:1, pp. 41-50.
- Waldman, Michael. 1984. "Job Assignments, Signaling and Efficiency," *Rand J. Econ.* 15:2, pp. 255-67.

- . 1990. "Up-or-Out Contracts: A Signaling Perspective," *J. Labor Econ.* 8:2, pp. 230–50.
- Welch, Ivo. 1989. "Seasoned Offerings, Imitation Costs, and the Underpricing of Initial Public Offerings," *J. Finance* 44:2, pp. 421–49.
- Weiss, Andrew. 1983. "A Sorting-cum-learning Model of Education," *J. Polit. Econ.* 91:3, pp. 420–42.
- Wernerfelt, Birger. 1988. "Umbrella Branding as a Signal of New Product Quality: An Example of Signaling by Posting a Bond," *Rand J. Econ.* 19:3, pp. 458–66.
- Williams, Joseph. 1988. "Efficient Signaling with Dividends, Investment, and Stock Repurchases," *J. Finance* 43:3, pp. 737–47.
- Wiener, Joshua L. 1985. "Are Warranties Accurate Signals of Product Reliability?" *J. Cons. Res.* 12:2, pp. 245–50.
- Wilson, Charles A. 1977. "A Model of Insurance Markets with Incomplete Information," *J. Econ. Theory* 16:2, pp. 167–207.
- Wolpin, Kenneth I. 1977. "Education and Screening," *Amer. Econ. Rev.* 67:5, pp. 949–58.
- Young, H. Peyton. 1993. "The Evolution of Conventions," *Econometrica* 61:1, pp. 57–84.