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"Wage Equations and Education Policy"

by

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I. Introduction:

One of the most widely estimated regression equations in economics is that of the earnings or wage function, which relates a measure of market remuneration (e.g., hourly wage rates, annual earnings) to measures of human capital stocks such as completed schooling and market work experience.[1] In the first half of this paper, I address two related questions: (1) What interpretation should be given to the wage equation? and (2) Why should we care about estimating it?

Twenty-five years ago Zvi Griliches, in his 1975 Presidential Address to the World Congress of the Econometric Society, raised the first question of interpretation, together with several others that were concerned with the appropriate specification and estimation of the wage function.[2] In that address, Griliches chose to adopt the competitive market - human capital production interpretation of Ben-Porath (1967), in which the wage an individual is offered is the product of the competitively determined skill rental price and the amount of human capital or skill units cumulatively produced by and thus embodied in the individual.[3] About a decade later, Heckman and Sedlacek (1985) and Willis (1986) extended the competitive market - human

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[1] I will generally refer to "wages" as opposed to "earnings" because the former has the connotation of a market price for labor.

[2] "Estimating the Returns to Schooling: Some Econometric Problems," Econometrica 45 (1), January, 1977.

[3] In the Ben-Porath model of human capital accumulation, individuals optimally choose a fraction of their skill units to produce additional skill, forgoing wage compensation for those units used in on-the-job investment. This contrasts with the notion that skills are acquired through a process of learning by doing in which skills are produced jointly with output. Learning by doing is not necessarily a costless activity if there are alternative uses for the time spent on the job, e.g., in the household sector or in alternative jobs.

capital production interpretation of the wage function to a multi-dimensional skill setting, formally incorporating the self-selection model of Roy (1951) to the choice of employment sector in the former case and to the choice of occupation cum schooling in the latter.[4] More recently, Keane and Wolpin (1997) extended and generalized the Heckman and Sedlaek and Willis papers to a dynamic setting of schooling, employment and occupational choice, adopting as well the competitive market - human capital production paradigm.

In contrast to the development and estimation of models that embed wage functions within a formal choice structure, as exemplified by these papers, over the past 40 years or so there has been a continuing effort to pin down estimates of wage function parameters as an end in itself. Given this sustained effort, the existence of a substantial payoff to identifying the parameters of the wage function, such as the schooling coefficient in a log wage equation, would appear to be self-evident. I pose the second question because it seems to me useful to rethink that enterprise.

The short answer to both questions, that of the interpretation of wage equations and that of the value in estimating them, is that it depends on the underlying economic model. The most direct example is where the paradigms concerning the origin of human capital differences are orthogonal, as in the productivity enhancing vs. signaling models of schooling.[5] What is (hopefully) less obvious is that even within a human capital production paradigm, in which

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[4] Heckman and Sedlacek did not model schooling choice. Willis did not model post-schooling human capital investment. However, Willis and Rosen (1979), which was the precursor, did allow for exogenous wage growth with age.

[5] For a recent creative attempt at empirically disentangling these seemingly observationally equivalent explanations see Fang (1999).

schooling for example directly augments skills, the schooling coefficient may have different interpretations depending on the economic environment that is assumed. In this paper, I demonstrate this point by contrasting the interpretation of wage equation parameters that arises in a single-skill model under the assumption of a competitive equilibrium in the skill market to that which arises in the wage-posting equilibrium search model of Mortensen (1990) and Burdett and Mortensen (1998). In the competitive model, wage parameters directly recover fundamental skill production parameters. In the wage posting model, the same parameters recover composites of skill production and other fundamental parameters of the model, those of the job search technology and the opportunity cost of time; the mapping from skills to wages is not direct.

The contrast between the competitive and wage-posting models is also illuminating with respect to the second question concerning the value in knowing the parameters of the wage equation. In the simplest single-skill competitive-equilibrium model of wage determination, in which schooling produces skill and is subject to choice, given the interest rate, the only fundamental parameters that determine schooling are those that also determine wages. Thus, knowledge of wage equation parameters alone is sufficient to perform counterfactual experiments, such as determining the impact on schooling of subsidizing the borrowing interest rate or of providing a college tuition subsidy. In the equilibrium search model, as noted, the wage equation identifies only a composite of the fundamental parameters.[6] It is, therefore, not possible solely with knowledge of wage equation parameters to perform counterfactual experiments in

[6] The fundamental choices in the search model context are with respect to unemployment and employment durations and the prototypical policy experiment is to determine the impact on those durations of increasing unemployment benefits The fact that the two models differ in these fundamental ways is, however, not relevant to the basic point.

that model.[7]

The simplicity of the early models of schooling choice, in which comparative static results depend only on the parameters of a single wage equation, provides a rationale for concentrating on wage equation estimation *per se.* A second factor that has led to the surfeit of wage equation estimates, and the recent resurgence of IV- natural experiment approaches to its estimation, stems from the extremely difficult problem of accounting in estimation for the existence of "ability" heterogeneity.[8] The goal of that literature has been to obtain estimates of wage equation parameters that are free of ability bias and the rationale of the natural experiment approach to uncover exogenous sources of variation in wage determinants. Yet, resolving the ability bias issue through the use of instruments or otherwise would, in richer choice models, still allow for the identification of only a part of the relevant structure necessary to perform counterfactual policy experiments.

The development and structural empirical implementation of richer choice models within the human capital production framework have been slow, despite the potentially large payoff in understanding behavior and in the estimation of the effects of policy interventions. When models that relax some of the assumptions of the simple schooling choice model have been estimated, they have generally found that the extensions are empirically important. Aside from their

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[7] Although my primary concern is not with estimation issues, it is true that prior knowledge of wage equation parameters would improve the efficiency of the estimates of the rest of the model's parameters.

[8] As I have pointed out in a recent paper with Mark Rosenzweig (1999), the interpretation of the estimates of wage equation parameters using instrumental variables based on natural experiments, presumed to be random, requires a theoretical model that specifically spells out the assumptions of how such instruments are related to underlying behavior.

methodological contributions, an important result from the early structural empirical papers of Willis and Rosen (1979) and Heckman and Sedlacek (1985) was the demonstration of the empirical relevance of comparative advantage in skills. Later papers by myself and Michael Keane, building on these early contributions, confirm that finding and demonstrate its importance for understanding the impact of education policies aimed at increasing school attainment and improving labor market outcomes.

The second half of the paper is devoted primarily to the consideration of one such policy, changes in college tuition costs. A large literature exists that attempts to estimate the impact of increasing college tuition costs on college enrollment within a non-structural empirical framework. In that literature, wage payoffs, and thus wage equation parameters, are only implicitly incorporated. It is not my purpose to survey the methodology and findings of that literature in detail, but rather to contrast that literature to the recent structural empirical literature mentioned above. I review the findings of the structural literature, which formally embeds preferences and technology, i.e., human capital production cum wage functions, and show how they help to interpret the behavioral responses estimated in the non-structural literature and how they can also be used to quantify the impact of alternative education policies.

Two examples, discussed in more detail below, will suffice. In Keane and Wolpin (1997), school attainment is shown to respond significantly to college tuition subsidies, consistent with the non-structural literature, but to have only a negligible impact on market wages. The reason for this result is due to (unobserved) heterogeneity in pre-market skills, occupation-specific skills determined prior to age 16 (comparative advantages that are either innate or produced within the family or that are due to the differential quality of schools attended up to that age).

As a second example, consider the general finding in the non-structural literature that tuition effects are larger for those from lower socioeconomic backgrounds. This result has led researchers to infer the existence of important borrowing constraints in the financing of higher education. Keane and Wolpin (1999b), in an extension of the preceding paper that allows for multiple methods of financing higher education, through the use of own assets, through working while attending school, through parental transfers and through external borrowing, show that such an inference is not necessarily warranted. Consistent with the previous research, they find that the responsiveness to changes in tuition costs declines with parental education and, seemingly consistent with the inference drawn from that result, that financing a significant portion of college costs through external borrowing is infeasible. However, because of the existence of heterogeneity in pre-market skills, they also find that relaxing borrowing constraints leads to only a negligible impact on school attainment.

The structural literature reviewed up to this point measures the impact of tuition changes assuming that skill prices are unaffected by them, that is, they measure partial rather than general equilibrium effects. However, policies that increase school attainment will reduce skill prices and thus reduce the incentive to acquire market skills. Two recent efforts, the first by Heckman, Lochner and Taber (1998, 1999) and another by Lee (2000), have developed and empirically implemented methodologies for the estimation of general equilibrium models of schooling choice, and used them to assess the extent to which partial equilibrium effects of tuition changes are misleading, These efforts differ in important ways and lead to quite different results. Heckman, Lochner and Taber (1999) find that the partial equilibrium effect of a change in college tuition overstates general equilibrium effects by about a factor of ten. On the other hand, Lee finds that partial equilibrium effects of a college tuition subsidy overstate general equilibrium effects by at most 10 percent.

II. Interpreting Wage Equations:

Essentially all empirical wage equations take the the linear form:

$$(1)\quad \log w = s(X;\beta) + \epsilon ,$$

where the X's are observable wage "determinants", β is a vector of parameters and ϵ accounts for unobservable wage determinants and for measurement error. The expectation of (1) for any X represents the mean of the distribution of wages *offered* to an individual with observable characteristics X. The human capital framework generates (1) as the equilibrium wage determined in a competitive and frictionless labor market. A quite different paradigm, one not usually associated with the human capital literature, generates (1) as the equilibrium outcome of labor market search on the part of workers and firms. These two economic models demonstrate an interesting contrast in the interpretation of (1) and in the usefulness of estimating its parameters.

A. The Wage Equation in a Competitive Model

The simplest version of the competitive model assumes a single homogenous productive skill in which workers are perfect substitutes in skill units.[9] Letting S_t be the aggregate number of units of skill used in production at calendar time t, i.e., the sum of skill units over workers, and

[9] Griliches (1977) explicitly derived the log wage equation in this single skill setting. The multi-skill analog is found in Heckman and Sedlacek (1985) and in Willis (1986), both of which have their roots in Roy(1951). Many of the same points made here are contained in those papers and I will not further delineate individual contributions. See in addition Heckman, Layne-Farrar and Todd (1996)).

K_t the aggregate stock of physical capital at time t, aggregate output at t is given by the constant returns to scale production function

$$(2) \quad Y_t = F(S_t, K_t; \theta_t),$$

where θ_t is a vector of production function parameters that may evolve with time and where (2) exhibits diminishing returns in each input. If aggregate skill over workers in the economy at time t is S_t^*, then for a given capital stock, the competitive assumption implies that the rental price per unit of skill at time t, r_t, is the marginal product of skill evaluated at S_t^*, i.e.,

$$(3) \quad r(S_t^*, K_t; \theta_t) = \frac{\partial F}{\partial S_t}\Big|_{S_t = S_t^*}.$$

An individual j who has s_{ja} units of skill at age a will receive a wage offer at time t, w_{jat}, given by the product of r_t and s_{ja}. Upon taking logs, the equilibrium wage offer function, i.e., the wage offered to an individual with s_{ja} units of skill at time t, is given by

$$(4) \quad \log[w(s_{ja}; r_t)] = \log(r_t) + \log(s_{ja}).$$

To complete the competitive equilibrium model, it is necessary to specify a model for the supply of skill units to the labor market.[10] There are two related issues in determining skill supply: (i) the amount of skill possessed by the individuals in the economy and (ii) if skill amounts are heterogeneous, the identities of the individuals who participate in the labor market and thus supply their skills to the market.

Ben Porath (1967), following Becker (1964) and Mincer (1958, 1962), provided the first formalization of the acquisition of skills within an explicit optimization framework. The essential idea was that human capital is produced according to some technology that combines an

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[10] It is, of course, also necessary to specify a model of physical capital accumulation. The discussion assumes that physical capital evolves exogenously.

individual's time with purchased goods. In the production function framework, the determinants of skill at any age would consist of all skill producing activities and complementary goods up to that age, beginning at least from conception (and therefore including parental behaviors, such as the mother's smoking behavior during pregnancy, and the time parents spend reading to their children at various ages, as well as the quantity and quality of formal schooling and training on the job), plus a genetically determined skill endowment, usually referred to as ability.[11]

A basic result from Ben-Porath was that individuals would optimally specialize in human capital production early in the life cycle, when an individual's stock of human capital was low, but, after some point, human capital production would decline with age. Mincer (1974) used that result to derive a wage function of the form,

$$(5)\quad \log(w_{ja}) = \beta_0 + \beta_1 E_{ja} + \beta_2 P_{ja} - \beta_3 P_{ja}^2 + \epsilon_{ja}.$$

where, E, school attainment, and P, work experience, are intended to capture all of the time and goods investments used in the production of skills given the difficulty of directly measuring inputs, as Ben-Porath noted.

The wage, and thus, indirectly, market-valued skill, feasibly can be observed only at the first age a market wage is offered, say a_0.[12] The amount of skill possessed at that age, pre-market skills, is the sum of the individual's skill endowment and of the amount of skill produced up to that age. It is convenient to distinguish between pre-market skills produced through formal schooling and pre-market skills produced outside of school (e.g., through investments made by

[11] Given the inherent non-observability of skill, ability is assumed to be measured in skill units.

[12] This age may depend on both technology and on legal restrictions.

the parents and by the child). I denote the latter by s_0.

A wage function consistent with Mincer's formulation is easily derived from the competitive skill market model. If the skill production function takes the form, $s_{ja} = s_{j0}\exp[\beta_1 E_{ja} + \beta_2 P_{ja} - \beta_3 P_{ja}^2 + \epsilon_{ja}]$, (4) can be written as

$$(6) \quad \log(w_{jat}) = \log(r_t) + \log(s_{j0}) + \beta_1 E_{ja} + \beta_2 P_{ja} - \beta_3 P_{ja}^2 + \epsilon_{ja}.$$

As (6) indicates, the constant term in the Mincer formulation can be interpreted as a composite of (i) the skill rental price, which depends on calendar time through changes in the aggregate skill supply and in the capital stock, and through permanent changes in technology or transitory production shocks, and (ii) the level of the individual's (non-school) pre-market skills, which may differ among individuals either because of genetic endowment or family investment behavior.[13] Shocks to wages, ϵ_a, other than through aggregate production shocks incorporated in the rental price, reflect idiosyncratic shocks to skills (e.g., random mental or physical lapses or enhancements). In this framework, the effect of school attainment on the wage is fixed by the technology of the educational system in producing market valued skills and does not have the interpretation of an internal rate of return.[14] Likewise, the effect of work experience on the wage

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[13] School-produced pre-market skills are accounted for in $\beta_1 E_a = \beta_1 E_0 + \beta_1(E_a - E_0)$, where E_0 is schooling at a_0. Endowed ability, in addition to being a component of pre-market skills, may also augment the amount of skill produced by additional schooling, work experience or pre-market non-school investments, leading to interaction terms in (5). This point is explicit in the specification of the human capital production function in Ben-Porath (1967) and was also made by Griliches (1977) in referring to a wage specification like (5). The existence of these interaction effects has become an important issue in the "treatment effects" literature, e.g., see Manski (1997), Heckman (1997) and Heckman and Vytlacil (1999).

[14] Heckman and Sedlacek (1985) use this observation to rationalize the relative constancy of the schooling coefficient over time in the face of large changes in aggregate schooling levels.

is fixed by the technology of skill acquisition on the job, i.e., by learning by doing. [15]

To complete the specification requires an explicit model of schooling, work decisions and pre-market skill acquisition. The incorporation of work decisions is particularly important for estimation because wage offers are only observed for individuals who work. I will return to this task, and to the implications of this modeling for estimation, after presenting a wage determination model in which there are labor market search frictions and which leads to a quite different interpretation of the parameters of the wage function.

B. The Wage Equation in the Burdett-Mortensen Equilibrium Search Model

In contrast to the interpretation of (6) as the outcome of a frictionless competitive equilibrium in unobservable labor quality or skill units, wage equations that arise from equilibrium search models are based on the existence of search frictions. In the Burdett-Mortensen model, firms post wages that are revealed to potential workers when they meet. Workers engage in search both while unemployed and while working.[16] All potential workers and all firms are identical. A steady state equilibrium wage distribution is generated as firms that post higher wages nevertheless earn the same monopsony rents as firms that post lower wages because they attract more workers, i.e., rent per worker times the number of workers is equalized across firms. The model generates a unique continuous wage offer density.

Unemployed workers solve a standard (infinite horizon - discrete time) job search model

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[15] Economic theory is not a useful guide for the manner in which inputs, schooling and work histories, should enter the skill production function.

[16] There are a number of excellent surveys of this literature, e.g., see Mortensen and Pissarides (1999) or Vandenberg (1999).

To maintain the parallel with the competitive model, as well as to conform to the empirical literature on estimating wage functions, consider a first-order approximation to the mean of the log wage, which takes the general form,

$$(13)\quad \log(w_j) = \gamma'_0(\lambda_0,\lambda_1,\delta,b) + \gamma'_1(\lambda_0,\lambda_1,\delta,b)\beta_1 E_j + \epsilon'_j .$$

Ignoring approximation error, analogously $E(\epsilon'_j|E_j) = 0$.

C. The Schooling Coefficient

There is an enormous literature whose goal is to estimate the schooling coefficient in Mincer-type wage equations. As is evident from a comparison of (6) and (13), however, its interpretation is quite different depending on which of the two labor market models is adopted. In the competitive model, knowledge of the schooling coefficient in (6), i.e. of the (percentage) effect of incremental increases in schooling on the wage, recovers the effect of school attainment on skill production, a fundamental structural parameter. In the wage posting model, however, knowledge of the schooling coefficient recovers a composite of the effect of school attainment on skill production (normalizing product price to unity), of the parameters describing the worker-firm meeting technology, of the job separation rate and of the (common) level of unemployment income plus monetary equivalent leisure value. It is thus necessary to combine wage data with other information in order to recover the schooling-skill relationship.

In contrast to the human capital literature, the estimation of wage offer equations, and in particular, the estimation of the schooling-skill relationship, has not been a singular goal of the equilibrium search literature. Indeed, given the identification problem associated with estimating the schooling-skill relationship from knowledge only of the wage equation parameters, estimating the wage offer function by itself is clearly fruitless for that purpose.[25]

In the competitive equilibrium model, the schooling coefficient identifies a single structural parameter of the skill production function. In early schooling models, it was the case that knowledge of that parameter was sufficient to draw policy implications. In the prototypical model in which (i) individuals maximize their present value of lifetime (non-stochastic) earnings, (ii) individuals work in all periods after completing school (and for a fixed period independent of schooling), (iii) the only cost of schooling is foregone earnings ($c = 0$) and (iv) there is a fixed borrowing rate of interest, the optimal level of schooling is simply given by the condition that the marginal percentage effect of schooling on wages (equal to the percentage increase in skill) is equal to the borrowing rate of interest. Thus, knowledge of the schooling coefficient is sufficient in those models to perform policy experiments that vary the borrowing rate.

To illustrate, consider the following stylized model of schooling choice.[26] Suppose each individual enters school at a mandated school entry age a_e and must remain in school until a mandated minimum school leaving age that is perfectly enforced, assumed to be the initial age at which wage offers are received, a_0. Thus, school attainment at a_0, initial schooling, is $E_0 = a_0 - a_e$, and is not subject to choice. Assume also that the individual decides on whether to

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[25] The empirical implementation of equilibrium search models is a recent literature and has been structural in its methodology. The goal of that research has been twofold: (i) to determine whether the dispersion observed in wages for seemingly observationally equivalent individuals is consistent with the degree of dispersion that can be generated by equilibrium search models; and (ii) to determine the magnitude of the effects of wage and unemployment insurance policies on labor market transitions. See Eckstein and Wolpin (1990) and van den Berg and Ridder (1998) for examples.

[26] The model is in the spirit of the formulation in Mincer (1974). See also Becker's (1967) Woytinsky lecture, Rosen (1977), Willis (1986) and more recently Heckman (1997).

attend school for only one period beyond the school leaving age.[27] School attendance in that decision period (at age a_0) is denoted by $e_1 = 1$ and non attendance by $e_1 = 0$; completed schooling, at age $a_0 + 1$, E_1, is therefore either $E_0 + 1$ or E_0. An individual who decides not to attend school is assumed to work in that period and in all subsequent periods until the end of working life, a = A. An individual who attends school is precluded from working in that period, but is assumed to work in all subsequent periods, i.e., from $a_0 + 1$ to A+1.[28] In addition, there is assumed to be a direct cost of attending school, c. The skill rental price is assumed to be constant and idiosyncratic shocks to skills are ignored.

The individual is assumed to make the choice of whether or not to attend school according to which option maximizes the present discounted value of lifetime earnings. The present value of each alternative to individual j, assuming the wage equation takes the form (6), but ignoring for simplicity the stochastic component, $V_1(e_1=1|E_0,s_0)$ and $V_1(e_1=0|E_0,s_0)$, is given by:

$$\begin{aligned} V_1(e_1=1|E_0,s_0) &= \exp[\log r + \log s_0 + \beta_1(S_0+1)] \sum_{a=1}^{A+1} \delta^a \exp[\beta_2(a-1) - \beta_3(a-1)^2] - c, \\ V_1(e_1=0|E_0,s_0) &= \exp[\log r + \log s_0 + \beta_1 S_0] \sum_{a=0}^{A} \delta^a \exp[\beta_2 a - \beta_3 a^2], \end{aligned} \tag{14}$$

where $\delta = 1/(1+i)$ is the discount factor and i the interest rate. The decision rule is to attend school if $V_1(e_1=1|E_0,s_0) \geq V_1(e_1=0|E_0,s_0)$, which reduces to

[27] The discrete nature of the choice parallels the sequential decision models discussed below.

[28] Allowing the working life to be independent of schooling simplifies the school attendance decision rule.

$$(15)\quad \begin{aligned} e_1 &= 1 \quad \text{if} \quad \beta_1 \geq i + \frac{c}{V_1(e_1=0|E_0,s_0)}, \\ e_1 &= 0 \qquad \text{otherwise.} \end{aligned}$$

Thus, the individual attends school if the percentage increase in the wage from attending school is sufficiently greater than the interest rate, or, equivalently, if the incremental income flow per unit time obtained from attending school net of the cost of tuition exceeds the income flow obtained from investing initial wealth at the market rate of interest.[29]

The schooling decision in this model depends on the level of pre-market skills (as defined, inclusive of "ability") and initial schooling, as well as on the interest rate. Individuals with a greater level of either pre-market skills or initial schooling, and thus greater initial wealth, $V_1(e_1=0|E_0,s_0)$, will be more likely to obtain the additional period of schooling. Indeed, given that the present value of earnings is increasing monotonically in pre-market skills, there exists a unique cut-off value below which $e_1=0$ is optimal and above which $e_1=1$ is optimal (for any value of initial schooling). Further, under the maintained assumption that individuals work in each period after completing school up to an exogenous retirement age (that is independent of completed schooling) work experience is independent of pre-market skills.

D. A Brief Digression: Estimating the Schooling Coefficient Using Natural Experiments

This simple theory has important implications for estimation. Clearly, estimation of (6) founders on the problem of measuring pre-market skills. The search for methods of obtaining a

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[29] In deriving (15), we use the approximation $\ln(1+x) \approx x$ for x equal to the interest rate and for x equal to the ratio of the direct cost of schooling to the present value of earnings when $e_0=0$.

consistent estimate of the schooling coefficient in this setting has been ongoing for several decades. One class of such methods that has recently gained renewed attention relies on the use of so-called natural experiments.[30] The general argument is that naturally occurring events that are by their nature random can be used as instrumental variables to identify important economic parameters, such as the schooling effect on wages. Angrist and Krueger (1991) use information on month of birth together with state-level school entry and school leaving age requirements to estimate the schooling coefficient. The idea is that two, otherwise identical, individuals residing in the same state whose birthdays differ by as little as one day may nevertheless have entered school a year apart. Given the difference in age at entry, their school completion levels would likely differ given that they must differ by a year at the minimum school leaving age.

The schooling model implies that there will indeed be a behavioral response to the additional schooling completed at a_0. From the decision rule (15) it can be seen that an individual who entered at an earlier age, and thus had completed more schooling at a_0, would not only have that additional year but also would be more likely to attend school after the minimum school leaving age.[31] Thus, month of birth should be related to completed schooling through its impact on age at entry. It would seem, then, that the presumably inherent randomness in month of birth would make it an ideal instrument for estimating the schooling coefficient.

A critical assumption, however, is that the variation created in age at entry due to

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[30] Rosenzweig and Wolpin (1999) review the literature, restricting their attention to the use of random events that arise in nature, what they call "natural" natural experiments.

[31] As noted, the reason for this is that, as with pre-market skills, initial schooling increases initial wealth which increases the propensity to obtain additional schooling. This result is obviously sensitive to the assumption that the impact of schooling on log skill is linear.

differences in month of birth is unrelated to variation in pre-market skills (inclusive of the ability endowment) and to variation in work experience. With respect to pre-market skills, it is plausible that children whose entry is delayed will not have the same skills upon entry as those who were not delayed. Parental investment behavior would presumably respond to the delayed age at entry. If, for example, skills that would have been acquired in school are acquired in the home or in pre-school, the instrumental variables estimator of the schooling coefficient based on month of birth would potentially understate the true schooling effect on skills.[32]

The model also assumed that individuals supply their labor inelastically in all post-schooling years. If, instead, individuals make labor supply decisions over their life cycles, it will generally be true that initial schooling, and thus age at school entry, will affect labor supply at post-schooling ages and thus be related to work experience. The reason is simply that because age at entry affects completed schooling, which itself affects wage offers, age at entry will also affect work decisions at all post-schooling ages.[33] Thus, the IV estimator based on month of birth (m) is

$$(16) \quad \frac{\partial \ln w_a/\partial m}{\partial E_a/\partial m} = \beta_1 + \frac{\partial s_0/\partial m + \beta_2 \partial P_a/\partial m}{\partial E_a/\partial m},$$

where, for convenience, we have assumed the experience effect on wages is linear. As seen in (16), the interpretation of instrumental variables estimators, even those based on arguably

[32] It is possible that the schooling-skill production function is such that the additional skills at school entry are irrelevant.

[33] As Rosenzweig and Wolpin (1999) show, the bias due to the schooling-experience relationship changes with age. At ages close to the school leaving age, those with more schooling have less work experience, while at later ages the more schooled, who are more likely to participate and work more hours when they do participate, have more experience.

random events, requires the researcher to specify a behavioral model inclusive of the role that the instrument plays.

III. Extensions of the Competitive Skill Market Equilibrium Model

The competitive skill market equilibrium model has been the foundation for many applications in labor economics, although it is often not explicitly stated. There is surprisingly little empirical work on estimating wage equations that has appealed to models beyond the simple version of the schooling-skill model presented above. Yet, when models that relax some of the assumptions of that model have been estimated, they have generally found those extensions to be empirically important. The primary extension has been to incorporate self-selection in a multi-dimensional skill setting along the lines of the Roy (1951) model.

A. Willis and Rosen (1979)

The first important extension, by Willis and Rosen (1979), allows for heterogenous skills in a schooling choice model. Following the interpretation in Willis (1986), suppose that there are two occupations in the economy, white-collar (wc) and blue-collar (bc), and that in order to enter the wc occupation one must have, using previous notation, $E_0 + 1$ years of schooling. Thus, an individual j who decides not to attend school in the remaining period is concomitantly deciding to enter the bc occupation. An individual has pre-market skills given by the pair $(s_{0j}^{wc}, s_{0j}^{bc})$.[34] It is natural in this setting to assume that the marginal product of incremental schooling may differ for wc and bc skills. Thus, abstracting from wage growth arising from the accumulation of work experience, which is allowed for as exogenous in Willis and Rosen, an individual faces the

[34] Pre-market skills are, in their terminology, abilities.

following schedule of wage offers depending on the schooling decision the individual makes:

$$(17)\quad \begin{aligned} \log(w_j^{wc}) &= \log(r^{wc}) + \log(s_0^{wc}) + \beta_1^{wc}(E_0 + 1) + \epsilon_j^{wc} \text{ if } e_1 = 1, \\ \log(w_j^{bc}) &= \log(r^{bc}) + \log(s_0^{bc}) + \beta_1^{bc}E_0 + \epsilon_j^{bc} \text{ if } e_1 = 0, \end{aligned}$$

where the individual's pre-market skills have been decomposed into a population mean level and an individual-specific component, i.e., $s_{0j}^k = s_0^k + \epsilon_j^k$ for k=wc, bc, and where the r^k's are the respective competitively determined skill rental prices.[35]

The multi-skill model creates an important distinction between the impact of additional schooling on skills and its impact on wage offers. In the single skill model, the schooling parameter in the wage equation is equal to both the percentage increase in skills and the percentage increase in the wage due to an additional period of schooling. In the multi-skill setting, the former is occupation-specific and is given by the schooling parameters in (17), β_1^{wc} and β_1^{bc}, while the latter, reflecting also the return to the option of working in the wc occupation if one attends school, depends on all of the wage determinants in both occupations. In particular, the percentage change in the wage offer to a person randomly chosen from the population to attend school is

$$(18)\quad \frac{1}{w}\frac{\Delta w}{\Delta E} = \log\left(\frac{w^{wc}}{w^{bc}}\right) = \log\left(\frac{r^{wc}s_0^{wc}}{r^{bc}s_0^{bc}}\right) + (\beta_1^{wc} - \beta_1^{bc})E_0 + \beta_1^{wc}.$$

As (18) reveals, the schooling effect on wages in this case is a composite of the structural parameters of both wage offer functions (those of the underlying skill production functions), as

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[35] The aggregate production function in this case is $Y = F(S^{wc}, S^{bc}, K)$ with skill rental prices given by their respective marginal products evaluated at the equilibrium aggregate skill quantities and capital. Willis and Rosen did not explicitly embed the model within a market equilibrium setting.

well as the occupation-specific rental prices determined in general equilibrium. Knowledge of (18), obtained say from variation in initial schooling as in the Angrist-Krueger natural experiment, would not recover the impact of schooling on either wc or bc skills.

Because individuals differ in their wc and bc pre-market skills, the sample analog of (18) depends on how individuals sort themselves into schooling groups. The choice of occupation, and thus schooling, as in the single-skill model is based on comparing the respective present values of wages. Assuming the direct cost of schooling is zero (c=0) as in Willis and Rosen, the decision by individual j to attend school is given by:

$$
(19) \quad \begin{aligned} e_{1j} &= 1 \quad \text{iff} \quad \epsilon_{1j}^{wc} - \epsilon_{1j}^{bc} > i + \overline{\log(w^{wc})} - \overline{\log(w^{bc})}, \\ &= 0 \qquad\qquad \text{otherwise}. \end{aligned}
$$

Given this decision rule the sample analog of (18) is simply

$$
(20) \quad \left\{\frac{1}{w}\frac{dw}{dE}\right\}_{SAMPLE} = \left\{\frac{1}{w}\frac{dw}{dE}\right\}_{POP} + E(\epsilon_{1j}^{wc} | e_{1j}=1) - E(\epsilon_{1j}^{bc} | e_{1j}=0).
$$

As (20) reveals, the schooling effect that is estimated from sample wage differences can either overstate or understate the effect under random selection. For example, it will be overstated if those who select wc have higher than average wc pre-market skills and those who select bc have lower than average bc pre-market skills. Willis and Rosen find that those who attend school (college) have higher than average wc pre-market skills and those that do not attend have higher than average bc pre-market skills. From (20), that implies that the sign of the difference in the sample and population schooling effects is indeterminate in theory.[36] Based on

[36] Willis and Rosen empirically implement the model using data from the NBER-Thorndike sample. They employ a two-step estimation procedure with the additional

their empirical estimates, the random selection effect (18) is 9 percent while the sample effect (20) is 9.8 percent. Their estimates are the first to indicate empirically the existence of heterogeneity in pre-market skills, that is, comparative advantage in the labor market, a finding that has been replicated in more recent studies and that appears to have critically important implications for education policy.

B. Heckman and Sedlacek (1985)

Heckman and Sedlacek (1985) provide a second important extension of the Roy model, although they focused on sectoral rather than occupational choice and their direct concern was not with the schooling-skill relationship. Unlike Willis and Rosen, they embed the sectoral choice model within a market equilibrium setting. In addition, they allow for a non-market sector and, given that, assume that individuals maximize utility rather than wealth. As in Heckman and Sedlacek, consider the choice of working in two different sectors, manufacturing (m) and non-manufacturing (n), in post-schooling periods. In each such period, an individual j of age a at calendar time t receives a wage offer from each sector k, k= m, n, that takes the form:[37]

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assumptions that family background characteristics affect the borrowing rate of interest but not pre-market skills and that the idiosyncratic components of pre-market skills and the borrowing rate of interest are distributed as joint normal. The "ability" tests available in their data are taken to be observable measures of pre-market skills and are assumed to be unrelated to borrowing costs.

It will not serve my purpose to repeat identification arguments in Willis and Rosen. Identification in selection models has been the subject of intensive investigation for the last 25 years. Without minimizing its importance, my concern is rather with the substantive economic interpretations and implications of these models.

[37] This formulation of the sector-specific skill production functions differs from that in Heckman and Sedlacek, who adopt a more general Box-Cox formulation that nests the exponential form as used in obtaining (6) and which allows for non-normal errors.

$$\text{(21)} \quad \log(w_{jat}^{k}) = \log(r_t^{k}) + \log(s_0^{k}) + \beta_1^k E_{ja} + \beta_2^k P_{ja} - \beta_3^k P_{ja}^2 + \epsilon_{ja}^{k}.$$

Notice that work experience in one sector is assumed to be a perfect substitute for experience in the other sector.

Individuals are assumed to be static optimizers.[38] The utilities associated with the three choices, denoting the home sector as h, are assumed to be given by:

$$u_{jat}^{m} = \log(w_{jat}^{m}) + b^{m} + \xi_{ja}^{m},$$

$$\text{(22)} \quad u_{jat}^{n} = \log(w_{jat}^{n}) + b^{n} + \xi_{ja}^{n},$$

$$u_{ja}^{h} = b^{h} + \xi_{ja}^{h},$$

where the b's reflect the non-pecuniary values attached to each of the market sectors and to the non-market sector and the ξ's are their associated time-varying shocks.[39] At any age a, individuals choose the option with the highest utility. Heckman and Sedlacek substitute the log wage function into (22) and normalize the utility of the home alternative to zero.[40]

Following arguments in Heckman and Sedlacek, estimating (21) using data from repeated cross-sections, and accounting for sectoral choice, recovers the sum of the sector-specific skill

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[38] This assumption is not innocuous because if individuals did not completely discount the future they would take into account that working (in either sector) at any age increases work experience at all future ages.

[39] Heckman and Sedlacek jointly estimate the reduced form choice model together with the wage function, but do not impose the parameter restrictions arising from the fact that the wage parameters also enter the choice model. The reduced form approach to estimation, while more robust, does not allow the recovery of sector-specific non-pecuniary values. The structure given by (22) is consistent with their reduced form specification.

[40] Assuming a general variance-covariance structure, estimation also requires that one of the variances of the non-pecuniary preference plus wage shock be normalized to unity.

rental prices and pre-market skills.[41] Assuming that pre-market skills do not vary over cohorts, the time-series of skill rental prices for each sector can be estimated up to a normalization of one skill rental price in each sector to unity.[42] This insight avoids having to solve the model for aggregate skill quantities that are needed to determine equilibrium marginal skill products, and thus skill rental prices, which in turn, as they note, would require estimating the model on demographic groups that differ in any fundamental parameters.[43]

Like Willis and Rosen, Heckman and Sedlacek find evidence of comparative advantage. They estimate that a reduction in the demand for manufacturing sector workers increases the average skill level in manufacturing, as those with less of that sector-specific skill leave manufacturing. In addition, however, the average skill level in non-manufacturing is reduced as the new entrants from the manufacturing sector have lower non-manufacturing skills than those in the sector before the demand reduction.[44]

C. Keane and Wolpin (1997)

Keane and Wolpin (1997) extend the Roy model to a dynamic setting, combining features of both the Willis and Rosen and Heckman and Sedlacek models. In their model, at each age an individual chooses among five mutually exclusive alternatives: attend school (e), work in a

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[41] They use March Current Population Surveys from 1968-1981.

[42] As a validation of this approach, they demonstrate empirically that rental prices behave as one would expect from theory.

[43] Estimates are based on white males age 16 to 65. Skill rental prices are assumed to be identical for all demographic groups.

[44] In this context, comparative advantages are not those related only to pre-market skills, but reflect differences in schooling and work experience at the time of the demand shift.

white-collar (wc) occupation, work in a blue-collar occupation (bc), work in the military (ml) or remain at home (h). The following current period utility payoffs capture their essential features:

$$
(23)\quad
\begin{aligned}
u_{ja}^{k} &= w_{ja}^{k} + b^{k} \quad \text{for } k = wc, bc, \\
u_{ja}^{ml} &= w_{ja}^{ml}, \\
u_{ja}^{e} &= b_{j}^{e} - tc_{1} I(S_{ja} \geq 12) - tc_{2} I(S_{ja} \geq 16) + \xi_{ja}^{e}, \\
u_{ja}^{h} &= b_{j}^{h} + \xi_{ja}^{h},
\end{aligned}
$$

where, as above, the b's reflect the non-pecuniary components of the alternatives, tc_1 and tc_2 are parameters indicating tuition and other direct costs associated with college attendance and the incremental cost of graduate school attendance and $I(\cdot)$ is the indicator function set equal to one if the expression in the parentheses is true. Occupation-specific skill rental prices are assumed to be constant over time.[45]

Skill production functions are modified from the single skill model so as to account for their occupation-specific nature, namely, $s_{ja}^{k} = s_{j0}^{k} \exp[\beta_1^k E_{ja} + \beta_2^k P_{ja}^{k} - \beta_3^k (P_{ja}^{k})^2 + \epsilon_{ja}^{k}]$. In attempting to fit the wage (and choice) data, Keane and Wolpin found it necessary to augment the set of inputs of the occupation-specific skill production functions to include cross-experience effects (work experience accumulated in the wc and bc occupations enter in all three skill production functions), skill depreciation effects (whether worked in the same occupation in the previous period), a first-year experience effect (whether or not the individual ever worked previously in

[45] With longitudinal data that does not span the entire working lives of the sample, it is not possible to estimate the time-series of occupation-specific skill rental prices using year dummies as in Heckman and Sedlacek. With perfect foresight, all future rental prices enter into any contemporaneous decision.

the occupation), age (maturation) effects, and separate high school graduation and college graduation effects.[46]

Individuals are assumed to maximize the expected present discounted value of their remaining lifetime utility at each age starting from age 16, the assumed initial decision-making age, and ending at age 65, the assumed terminal age. Letting $V(\Omega_{ja})$ be the maximum expected present discounted utility given the state space Ω_{ja} and letting the choice set be ordered from 1 to 5, in the order as given in (23), with d_{ja}^k equal to one if alternative k is chosen and zero otherwise, then

$$(24) \quad V(\Omega_{ja}) = \max_{d_{ja}^k} E\left[\sum_{\tau=a}^{65} \delta^{\tau-a} \sum_{k=1}^{5} u_{ja}^k d_{ja}^k \mid \Omega_{ja}\right] .$$

The state space at age a consists of all factors, known to the individual at a, that affect current utilities or the probability distribution of future utilities.

The value function can be written as the maximum over alternative-specific value functions, $V^k(\Omega_{ja})$, each of which obeys the Bellman equation (Bellman, 1957):

$$(25) \quad V(\Omega_{ja}) = \max_{k} \{V^k(\Omega_{ja})\} ,$$

where

$$(26) \quad \begin{aligned} V^k(\Omega_{ja}) &= u_{ja}^k + \delta E[V(\Omega_{j,a+1}) \mid \Omega_{ja}, d_{ja}^k = 1] \qquad \text{for } a<65, \\ V^k(\Omega_{j,65}) &= u_{j,65}^k . \end{aligned}$$

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[46]In addition, they incorporate the following features (parameters) into the model they estimate: a monetary job-finding cost for civilian occupation employment that depends on whether the individual ever worked previously in the occupation, age effects on the net (of effort) consumption value of school attendance, separate reentry costs associated with returning to high school and to college, age effects on the utility of the home alternative, psychic values associated with earning high school and college diplomas and a cost of prematurely leaving the military, i.e., before completing two years of service.

The expectation in (26) is taken over the distribution of the random components of the state space at a+1conditional on the state space elements at a, i.e., over the unconditional distribution of the random shocks given serial independence. The predetermined state variables such as schooling and occupation-specific work experience evolve in a Markovian manner that is (conditionally) independent of the shocks. There is no closed form representation of the solution. Keane and Wolpin use a numerical solution method based on an approximation method developed in an earlier paper (Keane and Wolpin (1994)).[47]

Individuals are assumed to be heterogeneous in their occupation-specific pre-market civilian skills (s_{j0}^{k} for k=wc, bc) and in their school and home non-pecuniary valuations (b_j^e and b_j^h). It is assumed that such population heterogeneity can be completely characterized by a fixed number (J) of types of individuals each occurring in the population with probability π_j. Each type is uniquely described by a vector of pre-market skills and non-pecuniary valuations. In addition to differing at age 16 in these characteristics, there are also differences in completed schooling levels at age 16. As is well known (Heckman (1981)), to the extent that this observable initial condition is the result of the same or closely related optimization problem that determines future choices, the initial condition will in general not be exogenous. Keane and Wolpin make the assumption that initial schooling is exogenous conditional on the unobservable persistent initial conditions. The method of estimation is by simulated maximum likelihood and the data they use are from the 1979 youth cohort of the National Longitudinal Surveys of Labor Market Experience. Their estimates are restricted to white males.

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[47] For surveys of methods used in solving and estimating discrete choice dynamic programming problems, see Eckstein and Wolpin (1989) and Rust (1994, 1996).

As noted, a consistent empirical finding of the Willis and Rosen and Heckman and Sedlacek papers was that comparative advantage plays an important allocative role in the labor market. Workers self-select into occupations and into sectors based on their relative productivities. This is also the result in Keane and Wolpin.

Comparative advantages determined by age 16 lead to large differences in school attainment, in later labor market outcomes and in lifetime welfare. As shown in table 1, of the four distinct types that are identified in the estimation, one type, comprising 17 percent of the sample, completes about 4 more years of schooling than any of the others, over 16 years on average, and specializes in white-collar employment. A second type, comprising another 23 percent of the sample, complete, on average, 12 years of schooling and specializes in blue-collar employment. Expected lifetime utility (not shown) as measured from age 16 is about the same for the two types, although it is 20 percent higher for the first type as measured from age 26 as lifetime utility from that age becomes dominated by life cycle earnings paths. The third type, 39 percent of the sample, is the only type to enter the military. They also complete about 12 years of schooling and, given the shortness of the length of military service, spend most of their life in civilian employment, specializing as does type 2 in blue-collar employment. However, as compared to the second type, who have much the same schooling and employment patterns, because they have considerably lower age 16 levels of pre-market skills, their expected lifetime utility is only about three-fifths as great. The last type, the remaining 21 percent, also completes about 12 years of schooling on average, but spends about 40 percent of their lifetime in the home sector, about five times as much as any other group.[48]

As also seen in table 1, the difference in school attainment that has already emerged by age 16, a difference of about 1.4 years, that is due to exogenous events unrelated to endowments, for example, illnesses that occurred in the past or date of birth that affects age at entry given the minimum school entry age, is magnified over time for two of the four types. Although the initial difference is reduced to about .8 years for type 1 individuals and is unchanged for type 3 individuals, the completed schooling difference increases to about 2 years for types 2 and 4.

Under the assumption that the four types capture all of the unobserved differences in pre-market endowments, it is possible to determine the extent to which conventional measures of family background are able to account for differences in lifetime utilities that arise from age 16 endowments.[49] In the baseline, the difference in expected lifetime utility between the first type (the highest) and the third type (the lowest) is estimated to be 188,000 (1987) dollars. In comparison, the difference for individuals whose mothers were college graduates relative to those whose mothers were high school dropouts is estimated to be 53,000 dollars, the difference for those who lived with both parents at age 14 relative to those who lived in a single parent home is 15,000 dollars and the difference between those whose parental income was more than twice the median relative to those less than one-half the median 66,000 dollars. While the association of expected lifetime utility with family income and mother's schooling appears to be

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[48] Given their age 16 endowment levels, however, their expected lifetime utility exceeds that of the third type who spend more time working in the market.

[49] These correlations may arise from family investment behavior as well as from the intergenerational transmission of innate talents.

strong, a regression of expected lifetime utility on those family background characteristics is reported to explain only 10 percent of the variation. Coupled with the fact that 90 percent of the total variation in expected lifetime utility is determined to be due to between-type variation, these family background characteristics actually are rather imperfect proxies for pre-market skills.

IV. The Use of Structural Estimation of Schooling Choice Models for the Evaluation of Education Policies:

In this section, I present evidence on the impact of three alternative policies to increase educational attainment: performance-based bonus schemes, college tuition subsidies and the relaxation of borrowing constraints. For each of these policy interventions, I present evidence obtained from papers that are based on structural estimates of the competitive equilibrium skill model. Where available, I also provide estimates from studies based on a non-structural estimation approach. I also present estimates from the structural studies on the longer-term impact of these policies on labor market outcomes. A common theme is that although education policies can influence significantly school completion levels, they cannot have large impacts on labor market success unless they also influence the level of pre-market skills.

These papers perform education policy experiments ignoring general equilibrium feedbacks. I briefly review two recent papers that have made a start at developing solution and estimation methods that can account for the impact of policy-induced skill supply responses on equilibrium skill rental prices.

Graduation Bonuses:

In the case of bonus schemes that provide monetary payments for high school and/or college graduation, which have been implemented in only a few instances and only on a small scale, available estimates come solely from the structural implementation of schooling choice models.[50] Keane and Wolpin (1999a) evaluate the effect of two graduation bonus schemes using the previous model. One such plan, which has been advocated recently by Robert Reich, the former Secretary of Labor, provides a $25,000 bonus for high school graduation to all youths whose parents earn less than 120 percent of the median household income. A second scheme seeks to equalize the schooling distributions of black and white males through the combined use of a high school graduation bonus and a college graduation bonus.

Keane and Wolpin estimated the model pooling data on black and white males from the NLSY. Interestingly, they found that observed differences in schooling and employment behavior by race could be accounted for solely by differences in the constant terms in the white- and blue-collar wage functions and by differences in type proportions. The simulated effects of the two graduation bonus experiments on schooling and labor market outcomes, based on the estimates from the pooled data, are reported in table 2.

As seen in the first two columns of the table, in the baseline simulation, black males complete one less year of schooling than do white males, 12.0 vs. 13.0, and earn 75 percent of white males at age 40 (74 percent in present discounted value over their lifetimes).[51] The second

[50] As I have discussed elsewhere in the context of the policy uses of discrete choice dynamic programming models (Wolpin (1997)), a major advantage of structural estimation is the ability it provides to perform counterfactual policy experiments that entail extrapolations outside of the current policy regime.

[51] The model is shown to fit the data well. The fit is contrasted to that of a model in which individuals solve a static optimization problem. Although the within-sample fit of the static model is only slightly worse than the fit of the forward-looking model, the static model out-of-sample forecasts are incredible, e.g., the average white-collar wage is forecasted to rise to $250,000 by age 50.

two columns report the effect of implementing the Reich proposal. The effect of that proposal is estimated to increase average schooling substantially, for white males by .5 years and for black males by .8 years. However, the effect of that plan is concentrated on high school graduation rates, reducing the proportion of white males who do not graduate from 26.7 percent to 7.6 percent and that of black males from 37.9 percent to 12.1 percent.[52]

While schooling is increased appreciably, the impact of the bonus on labor market outcomes is small for both races, although somewhat larger for blacks. For example, white-collar employment of white males increases at age 40 by only 2.5 percentage points, earnings at age 40 increases by less than one percent and the present value of lifetime earnings by less than 2 percent. Even though the skill production function estimates imply that an additional year of schooling increases white-collar wages by 7 percent and blue-collar wages by only 2 percent, those induced to obtain the additional schooling by the bonus are nevertheless, given their pre-market skills, still better off in blue-collar occupations and those that do enter the white-collar occupation do so with a lesser amount of white-collar pre-market skill.[53]

In the second experiment, reported in the last column of table 2, both high school and college graduation bonuses are provided to black males at levels that are sufficient to essentially equalize the black and white distributions of schooling (80 percent of the gap in mean school

[52] Notice, however, that almost half of those who graduate from high school due to the bonus go on to complete some college.

[53] This result is consistent with the findings in Cameron and Heckman (1998). Using a quite different framework, they find that those who are induced to attend college by a subsidy policy are of less ability than those who attend without the subsidy. They conclude that the ignoring heterogeneity will lead to an overstatement of the impact of such policies on labor market outcomes.

attainment is closed).[54] However, analogous to the Reich proposal, while the schooling gap is closed, the effects on labor market outcomes is quite small. For example, white-collar employment among whites still exceeds that of blacks at age 40 by 9.5 percentage points, the black-white male earnings gap at age 40 is reduced only from 25 to 22 percentage points and the difference in the present discounted value of lifetime earnings only by 4.8 percent. Race differences in age 16 endowments account for much of the remaining gap.[55]

Tuition Effects:

In contrast to a graduation bonus scheme, which rewards individuals for years of schooling that are completed, tuition subsidies are based only on attendance. It is more conventional in the non-structural literature to estimate tuition effects because tuition levels vary over time and cross-sectionally. Keane and Wolpin (1997) simulate the effect of an experiment that provides a tuition subsidy of approximately 50 percent for each year of college attendance.[56] They report an increase in mean schooling of .5 years, from 13.0 to 13.5 years, an increase in the proportion graduating from high school (without attending college) by 3.5 percentage points and

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[54] The exact bonuses are, in 1987 dollars, $6,250 for high school graduation and $15,000 for college graduation.

[55] Because the constant terms in wage functions are the sum of occupation-specific skill rental prices and age 16 endowments of pre-market skills, it is not possible to disentangle the role of discrimination as distinct from differences in pre-market skills. However, it is possible to establish an upper bound estimate of the component due to discrimination, which turns out to be around 30 percent.

[56] Keane and Wolpin treat college tuition as a parameter. It is estimated to be $4,186 (in 1987 dollars).

an increase in college graduation rates of 8.4 percentage points.[57]

The model on which these estimates is based is silent with respect to the financing of college costs. The assumption of linear utility implies that the capital market environment is irrelevant, essentially permitting individuals to make school attendance decisions independently of financing considerations. In another paper, Keane and Wolpin (1999b) drop the linear utility assumption and account explicitly for borrowing constraints. Uncollateralized borrowing is permitted, but is constrained to be less than some given amount, the net borrowing limit, that varies with age and other characteristics. The function describing the net borrowing limit is estimated. In addition, the borrowing rate of interest is not restricted to be equal to the lending rate. Several other potential mechanisms for financing college costs are modeled, through own savings, parental transfers and current earnings.

More realistically, in this model, individuals are assumed to make part- and full-time work and school attendance decisions and may work while attending school. Unobserved heterogeneity, as before, takes the form of there being a fixed number of types who differ in their pre-market skills, their net consumption value of school attendance and the value they attach to the home sector. Although there is only one occupation option, individuals may exhibit comparative advantages across work, school and home sectors. Parents make monetary transfers to co-resident children that depend on their own schooling and that may be greater when youths are attending college.

Although this model differs considerably from the previous one, the impact of a college

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[57] The increased high school graduation rate occurs because of the forward-looking nature of the model.

tuition subsidy is roughly the same magnitude. Subsidizing tuition costs fully would increase completed schooling by 1.1 years.[58] Interestingly, these estimates agree with those from the non-structural literature. Table 3 presents a summary of estimates of the percentage change in college enrollment rates induced by a tuition increase of $100 per year, the standard metric used for calibrating tuition effects in the literature. As seen, Leslie and Brinkman (1987), in a survey of 25 empirical studies based on cross-state or time-series variation in college costs, report the modal estimate of the response to a $100 tuition increase (in '82-'83 dollars) to be a 1.8 percent decline in the enrollment rate of 18-24 year olds. Other estimates range from a low of .8 percent for 18-24 year old whites to a high of 2.2 percent for 18-24 year old blacks (Kane, 1994). In Keane and Wolpin (1999b), the comparable effect is a decline of 1.2 percent.

Relaxing Borrowing Constraints:

As discussed in Keane and Wolpin (1999b), it is common also to report effects of tuition increases separately by the income quantiles of the youth's parents. These studies typically find much larger tuition effects for low income youth. As seen in table 3, for instance, St. John (1990) estimates that a $100 tuition increase (in '82-'83 dollars) lowers the enrollment rate of 18-19 year old high school graduates by roughly 0.85 percent. However, he also reports that the enrollment rate would drop by 1.1 percent for youths from families with income below $40,000, but only by .4 percent for youths from families with higher income. Manski and Wise (1983) find, for the same age group, that a $100 tuition increase (in '82-'83 dollars) leads to a large decline, by 3.6 percent, in the enrollment rate among youths whose parents are in (roughly) the bottom income

[58] The college tuition cost is estimated to be (in 1987 dollars) $3,673.

quintile, while they find much smaller effects for youth from higher income families. Based on more recent data, Kane (1994) estimates that a $100 increase (in '82-'83 dollars) leads to a decline in college enrollment rates of roughly 1.4, 1.0, 0.5 and 0.2 percent for 18-19 year old white male high school graduates whose parents are in the first through fourth income quantiles respectively.

The finding that tuition effects are inversely related to parental income has often been interpreted as evidence for the existence of borrowing constraints that have adverse consequences for college attendance (see, e.g., Kane (1999) p. 63). In the model estimated in Keane and Wolpin (1999b), borrowing constraints are found to be quite binding. The (net) debt limit is estimated to be very low, at most $1,000, and to differ only little by the individual's human capital. Financing college tuition through uncollateralized borrowing is therefore not feasible. In addition, consistent with the pattern found in the non-structural literature, Keane and Wolpin report that a simulated $100 annual tuition increase (in '82-'83 dollars) leads to declines in enrollment rates (for 18-19 year old high school graduates) of 2.2, 1.9, 1.5 and 0.8 percent, respectively, if the youth's parents are in each of four ascending education categories (both are high school dropouts, at least one is a high school graduate, at least one has some college, at least one is a college graduate). Thus, the model generates a pattern of larger percentage declines in enrollment for youth whose parents have lower SES.

On the surface, it would appear that the inference drawn in the non-structural literature, that borrowing constraints exist and limit college attendance of youths from less affluent families, is validated by the congruence of these two findings. However, when Keane and Wolpin simulate the impact of relaxing the borrowing constraints, by allowing youths to borrow the full tuition cost, they find that there is only a negligible increase in college attendance.[59] Instead, allowing college attendees to borrow the full amount of their tuition costs leads to a reduction in their propensity to work while attending school and to an increase in their consumption.[60] College attendance is limited not by borrowing constraints, but rather primarily by age-16 endowments of pre-market skills and/or preferences.[61]

V. General Equilibrium:

The policy effects described above assume that general equilibrium feedbacks are negligible. However, policies that serve to increase schooling levels, and thus the aggregate skill level, will reduce the skill rental price in equilibrium. Partial equilibrium estimates of the impact

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[59] Keane and Wolpin (1999b) also find that, on average youths receive a transfer from their parents, in excess of what is received when not attending college, sufficient to fully subsidize college tuition costs. The subsidy ranges from about one-half of the tuition cost for youths whose parents are the least educated (neither a high school graduate) to almost twice the tuition cost for youths whose parents are the most educated (at least one parent a college graduate). It might appear that it is because of the largesse of parents that relaxing borrowing constraints has only a minimal impact on college attendance. However, simulating the impact of relaxing the borrowing constraint in a regime where parents are assumed to provide no additional transfers to children who attend college leads to the same result.

[60] Cameron and Heckman (1998) reach a similar conclusion based on a sequential statistical decision model of schooling choice. They find that family income has only a small effect on college attendance conditional on long-term factors such as family background and permanent income. They conclude that short-term credit constraints are therefore unimportant in explaining schooling decisions. Cameron and Taber (2000) develop tests for the importance of borrowing constraints in schooling decisions based on the proposition that direct schooling costs would have a greater impact than opportunity costs if borrowing constraints were operative. As is consistent with the findings of Keane and Wolpin and Cameron and Heckman, they find no evidence that borrowing constraints play an important role.

[61] That is not to say that differentials in parental transfers are unimportant. However, as Keane and Wolpin report, equalizing parental transfers would reduce the difference in the mean schooling of youths whose parents are in the highest vs. the lowest education group only from 3.8 years to 2.6 years.

of those policies on schooling would, therefore, overstate the general equilibrium impact. There is at this point only limited evidence on the extent of the overstatement.

Consider the Keane and Wolpin (1997) framework in which occupation-specific skill rental prices are constant over time. A setting consistent with that assumption is one in which there are no aggregate production shocks and in which there is a stationary population with an unchanging age distribution. In that case, aggregate skill in an occupation at any calendar time is simply the sum of the skill amounts of individuals choosing to work in the occupation at that time. Rental prices are then given by the skill marginal products evaluated at aggregate skill levels. Equilibrium rental prices are those that yield the aggregate skill levels consistent with individual choices.

More concretely and for simplicity, assume that there is only a single occupation and that production is Cobb-Douglas, that is, $Y = A S^{\alpha} K^{1-\alpha}$. Aggregate skill is given by the sum of the skill levels over individuals, namely $S = \sum_a \sum_{j=1}^{N_a} s_{ja} = \sum_a \sum_{j=1}^{N_a} s_{0j} \exp[\beta_1 E_{ja} + \beta_2 P_{ja} - \beta_3 P_{ja}^2 + \epsilon_{ja}]$, where N_a is the number of individuals of age a in the population. As noted it is not possible to separately identify, from data on choices and wages, both the skill rental price and the level of pre-market skills. Moreover, given the non-observability of skill, the technology shifter, A, also cannot be identified. A baseline case can be established either by normalizing A or the rental price. Assuming A=1, a baseline equilibrium rental price can be established that induces a level of aggregate skill that equates the marginal product of skill to that rental price. The general equilibrium impact of a tuition subsidy on schooling is determined by resolving jointly for the equilibrium rental price and optimal choices.

Donghoon Lee (2000) has implemented this procedure in the multi-skill setting allowing as well for non-stationarity in population size, that is, for changing cohort size. Lee adopts an overlapping generations version of the occupational and schooling choice model of Keane and Wolpin (1997) assuming that individuals have perfect foresight about equilibrium outcomes, but imperfect foresight about their idiosyncratic shocks to preferences and skills. Each cohort therefore faces a known, but different, sequence of occupation-specific skill rental prices. Individuals are assumed to face exogenous cohort and age-specific fertility rates and a constant college tuition cost. Aggregate production at any calendar time depends on the aggregate level of white-collar skill, the aggregate level of blue-collar skill and capital. Capital grows exogenously at a known rate. The production function is Cobb-Douglas with time-varying factor shares (technology parameters) about which individuals also have perfect foresight.

Lee estimates the model using aggregate data from the 1968-1993 Current Population Surveys (CPS). The model is fit to the empirical moments of school enrollment rates, occupation-specific employment rates and educational attainment by age, year and sex and to wage moments by age, year, sex and educational attainment. As seen in table 3, the partial equilibrium effects are in line with those of other studies. Similar to Keane and Wolpin (1997), Lee finds that a 50 percent subsidy to college costs would increase completed schooling by .6 years for males (and by .9 for females). Further, the partial equilibrium effect of a $100 tuition increase reduces college enrollment rates by 1.12 percent for 18-19 year old males and by 1.34 percent for 18-24 year old males. General equilibrium effects on completed schooling for the 50 percent subsidy are 87 percent of the partial equilibrium effect for males and 93 percent for females, while they range from 92 to 95 percent of partial equilibrium effects on college enrollment rates for the 100 dollar tuition increase.

In an earlier series of papers, Heckman, Lochner and Taber (1998, 1999) perform a similar comparison based on a general equilibrium model with different characteristics. The data and estimation methods they adopt also differ significantly from Lee. As with Lee, I only briefly describe the essential features of their model and the estimation method. Specifically, in their model: (1) skill classes are defined by educational attainment; (2) in addition to making an initial discrete schooling decision, in each post-schooling period individuals explicitly decide on their human capital investment time on the job á la Ben- Porath; (3) individuals make savings decisions in each period; (4) labor is inelastically supplied in each period.

As they note, accounting in estimation for the restrictions that general equilibrium imposes given the structure of their model is not feasible with available data. In particular, estimation is hindered by the lack of micro-data on consumption and on investment time on the job. For that reason the procedure adopted for recovering the parameters of the model involves a combination of calibration based on results from existing studies and new estimation using both aggregate CPS data (over the period from 1963-1993) and longitudinal data from the NLSY.[62] As seen in table 3, the partial equilibrium effect of a 100 dollar increase in college tuition costs is 1.6 percent, well within the range of other studies and not much different from that of Lee or Keane and Wolpin. However, the general equilibrium effect is reduced by an order of magnitude, to 0.16 percent.

Clearly, the bound established by the Heckman, Lochner and Taber and Lee papers is extreme. Accounting for the divergence in their results is problematic because of the major

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[62] It is not possible to describe in limited space the often quite ingenious steps in the estimation procedure and I would simply refer the reader to the paper for details.

differences in their modeling and estimation approaches. Clearly, further study is warranted.

VI. **Conclusions**:

Within the competitive market - human capital production paradigm, in a setting in which there is a single homogenous skill, the wage equation is a fundamental structural relationship. Knowledge of its parameters, therefore, provides information useful in understanding human capital investment behavior and in analyzing the impact of policy interventions. Indeed, in early pioneering models of schooling choice, knowledge of the parameters of the wage equation were both necessary and sufficient to perform education policy analysis. However, as I have discussed, in richer models of schooling and on-the-job skill acquisition, such knowledge is necessary, but not sufficient.

Although it is not obvious that richer models are indeed necessary for evaluating specific policy interventions, models of schooling and employment choices which embed wage equations as part of a larger structure have yielded important empirical results and allow the evaluation of a wider range of policies. In those models, wage equation estimation is not an end in itself. It would seem to me fruitful to turn attention to refining and expanding behavioral models of human capital accumulation in both partial and general equilibrium contexts.

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Table 1
Selected Characteristics at Age 24 by Type:
Nine or Ten Years Initial Schooling

	Initial Schooling <=9				Initial Schooling>=10			
	Type 1	Type 2	Type 3	Type 4	Type 1	Type 2	Type 3	Type 4
Mean Schooling	15.6	10.6	10.9	11.0	16.4	12.5	12.4	13.0
Proportion in:								
White-Collar	.509	.123	.176	.060	.673	.236	.284	.155
Blue-Collar	.076	.775	.574	.388	.039	.687	.516	.441
Military	.000	.000	.151	.010	.000	.000	.116	.005
School	.416	.008	.013	.038	.239	.024	.025	.074
Home	.000	.095	.086	.505	.050	.053	.059	.325
Sample Proportion	.010	.051	.103	.090	.157	.177	.289	.123

Source: Keane and Wolpin (1997), Tables 11, 13

Table 2
Effect of School Performance-Based Bonuses on Completed Schooling and Labor Market Success by Race

	Baseline		Reich Proposal[a]		Keane and Wolpin[b]
	White	Black	White	Black	Black
Mean Highest Grade Completed	13.0	12.0	13.5	12.8	12.8
% Highest Grade Completed					
<12	26.2	37.9	7.6	12.1	26.0
=12	29.6	31.5	39.6	47.8	31.6
≥13 and ≤15	19.1	17.9	26.2	26.4	16.2
≥16	25.1	12.8	26.7	15.8	26.1
Labor Market Outcomes at Age 40					
Annual Earnings	32,635	24,626	32,687	26,623	25,414
% Employed in White Collar	39.5	26.1	42.0	32.4	30.0
Blue-Collar	58.7	68.3	56.0	63.2	65.1
PDV Lifetime Earnings[c]	285,400	210,258	290,393	228,850	213,885

a. $25,000 bonus for high school graduation restricted to family income ≤120% of the median
b. $6,250 bonus for high school graduation, $15,000 for college graduation
c. Discounted to age 16

Source: Keane and Wolpin (1999a), various tables. Labor market effects for Reich proposal computed by author.

Table 3
Effects of College Tuition Changes on Schooling

	Tuition Change	Treatment Group	Schooling Effect
Partial Equilibrium			
1. Completed Schooling			
Keane and Wolpin (1997)	50% subsidy	white males NLSY cohort	.5 year increase
Keane and Wolpin (1999b)	80% subsidy	white males NLSY cohort	1.1 year increase
Lee (2000)	50% subsidy	males, females: 1957-1964 cohort	.5, .9 year increase
2. College Enrollment Rates			
Leslie and Brinkman (1987)	$100 increase in tuition [a]	18-24 year olds- various samples	1.8% decline
St. John (1990)	$100 increase in tuition [a]	18-19 year olds	0.9% decline
Kane (1994)	$100 increase in tuition [a, b]	18-19 year old white, black males	0.8%, 2.2% decline
Keane and Wolpin (1999b)	$100 increase in tuition [a, b]	18-19year old white males	1.3% decline
		18-24 year old white males	1.2% decline
Heckman, Lochner and Taber (1999)	$100 increase in tuition [a, b]	White males NLSY cohort	1.6% decline
Lee (2000)	$100 increase in tuition [a]	18-19 year old males, females	1.12%, 1.66% decline
		18-24 year old males, females 1957-1964 cohort	1.34%, 1.95% decline
General Equilibrium			
College Enrollment Rates			
Heckman, Lochner and Taber (1999)	$100 increase in tuition [a, b]	18-19 year old white males	0.16% decline
Lee (2000)	$100 increase in tuition [a]	18-19 year old males, females	1.05%, 1.52% decline
		18-24 year old males, females 1957-1964 cohort	1.27%, 1.86% decline

a. 1982-83 dollars
b. Adjusted for comparability