The O-Ring Sector and the Foolproof Sector: An explanation for cross-country income differences

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Abstract

Differences in worker skill cause modest differences in wages within a country, but are associated with massive differences in productivity across countries (Hanushek and Kimko, 2000). I build upon Kremer's (1993) O-ring theory of production to explain this stylized fact. I posit that there are two kinds of jobs: O-ring jobs where strategic complementarities to skill are large, and a diminishing-returns Foolproof sector, where two mediocre workers provide the same effective labor as one excellent worker. In equilibrium, an econometrician would only see small returns to skill within a country. In a world where countries vary only slightly in the average skill of workers, these assumptions are sufficient to generate massive differences in cross-country income inequality while generating only small amounts of intra-country income inequality. Implications for immigration policy, dual labor market theory, and border regions are discussed.

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Why do skill differences that matter so little for individuals appear to matter so much for nations? In this paper, I offer one answer to this question: I propose that some jobs within each country involve increasing returns to skill, while other jobs within the same country do not. In equilibrium this is enough to generate small within-country returns to "skill" or "labor quality" or "IQ" while generating massive differences in productivity across countries.

I contend that the average wage within a given country is pinned down by the productivity of its best workers in a Kremer-style (1993) "O-ring" sector. In this sector, high-skilled workers perform tasks that depend on strategic complementarities in production. Other less-skilled workers in that same country aren't good enough to work in this increasing-returns "O-ring" sector–at least not without taking a massive wage cut. But in equilibrium, they *can* work in a conventional, diminishing-returns-to-labor "Foolproof" sector, earning only slightly less than the high-skilled workers in their own country. Crucially, high-skilled workers can move between the O-ring and Foolproof sectors. The key assumption of this model is that the wage of high-skilled workers must be equal across the two sectors, a simple invocation of the law of one price.

Under this model, within a given country, the less-skilled workers will earn only slightly less than the highly-skilled workers, since, after all, in the Foolproof sector high- and low-skilled workers are close substitutes (This high substitutability is the assumption implicitly used whenever economists use "average years of schooling" in productivity accounting exercises or growth regressions). But *across* countries, a *nation* whose best workers are slightly lower in quality will be *much* less productive, since it means that workers in that nation's "O-ring" or "weak link" sector will produce much less.

This model builds on the idea that there are two kinds of jobs: Some jobs require a number of production steps where the product's value can be destroyed by one "weak link," (e.g., advanced manufacturing, high-level law or finance), while other jobs can be done quite well either by isolated individuals or by a combination of workers with a variety of skill levels (e.g., many personal services, food preparation, routine law and banking matters).

In general equilibrium the model generates results that match the data: Looking *within* a given country, the (modest) wage variance across workers will be driven entirely by differences within the Foolproof sector. But looking *across* countries, productivity variance will be driven by (large) differences across the O-ring sectors.

But of course, all of this is for naught if the first sentence of this paper poses an invalid question. Is there evidence that skills and abilities matter little for individuals but a lot for nations?

Yes. For example, Hanushek and Kimko (2000) look at how national math and science scores predict long-run economic performance across countries; famously, East Asian economies combine high math and science scores with good economic performance. The authors show that average national math and science scores are excellent predictors of large differences in long-term economic performance even if they omit East Asian economies from their sample.

More importantly, they also show that such scores are *weak* predictors of how much typical immigrants from those countries earn when they arrive in the U.S.. Immigrants from high-scoring countries indeed earn more than immigrants from low-scoring countries, but the differences are quantitatively modest. Combining these two results, they conclude:

> [T]he [cross-country] growth equation results are much larger than the corresponding results for individual earnings (Hanushek and Kimko, 2000, p. 1204).

Further, they find that these test score measures, which they consider indices of "labor quality," are more important than typical years-of-schooling measures for predicting cross-country economic performance:

> The growth model results…imply that *the externalities must be significantly stronger for quality than for quantity*. The estimated growth effect of one standard deviation of quality is larger than would be obtained from over nine years in average schooling (Hanushek and Kimko, 2000, p. 1204).

Jones and Schneider (forthcoming) find much the same when they use cross-country differences in average IQ scores rather than Hanushek and Kimko's math and science tests. Immigrants from high-average-IQ countries indeed earn more upon arrival in the U.S.. But while one IQ point predicts only one percent more U.S. income for an *individual* worker (a result supported by a variety of micro-level labor econometric evidence), a *country* with an average IQ score one point higher would be predicted to produce six to seven percent more output per worker (See Figures 1 and 2. Note that within a given country, one standard deviation in IQ is approximately 15 IQ points).

Separately, Jones and Schneider (2006) also find that once one controls for national average IQ in cross-country growth regressions, the statistical significance of education quantity measures is diminished, thus supporting Hanushek and Kimko's second contention that quality of labor matters more than quantity of education. Thus, Jones and Schneider support both of Hanushek and Kimko's claims: test scores matter more for nations than for individuals, and test scores matter more than education at the cross-country level.

Thus, in the model below, I will focus on showing how modest differences in "labor quality" will generate small intra-country differences, but large inter-country differences. Whether one considers math and science scores or Lynn and Vanhanen's (2002, 2006) national average IQ scores as the preferred measure of labor quality is irrelevant to the model's interpretation. I will omit discussion of the quantity of education, since it doesn't appear to predict disproportionate cross-country income differences.

I will begin by setting up a benchmark model with two production sectors and two levels of labor quality within a given country. In the model, I never appeal to exogenous cross-country productivity differences to explain cross-country income differences. I move on to an extensive discussion of the model's implications, and then work through some simple quantitative exercises that show that the model can explain real-world data. I next show that the model generalizes to a continuum of labor quality and to Kremer's own extended O-ring model that allows an endogenous choice of the length of the production process. I follow with a discussion of some of the model's implications for economic growth research, and conclude.

I. The Benchmark Case

A. Model

The O-ring production function is exactly that of Kremer (1993): Each firm combines an amount *k* of capital with a group of *n* workers to create output. Each worker performs her task accurately with a probability of *q*; another equivalent interpretation is that *q* is the fraction of "potential value" that a particular worker actually creates, taking the quality of other workers as given.

To illustrate, I will omit capital and total factor productivity for the moment, and assume that workers all have the same skill level. In this simplified version, a firm's output equals $q^n n$. The immediate implication of this O-ring technology is that small declines in average skill lead to big declines in productivity. For example, if every production process has two activities, and the workers perform them perfectly, then n=2, q=1, and total output = q*q*2=2. But if the same two-link process is used with two less-skilled workers of q=0.9, then total output = 0.9^2*2 =1.62. And of course, if production in the O-ring sector involves *many* links, then even if worker quality only declines slightly, the productivity decline can be massive. Real-world examples include the production of microchips and of high-end clothing; in the former case, a slightly-flawed product is literally worthless, while in the second case a slightly flawed product will sell for a steep discount at an outlet store.

Kremer shows that in equilibrium, workers within a given firm will only be combined with other workers of the same skill level–a fact that I make use of throughout this paper. This endogenous sorting of workers is the source of the "strategic complementarity" contained within the Kremer model.

In the model below, there will be a total of φ firms in the O-ring sector. The number φ will be determined by the free entry condition, which in the benchmark equilibrium will depend only on the supply of willing, high-skilled workers. Formally, output per firm, precisely following Kremer, is:

$$Y_{O/\varphi} = Bk^{\alpha}q^{n}n \qquad (1)$$

$Y_{O/\varphi}$ denotes O-ring sector output per firm. Here, B is an exogenous productivity factor *identical across countries*. In equilibrium, Kremer shows that the O-ring wage is simply a fraction (1-α) of per-firm output divided among the *n* workers, an outcome comparable to the standard Cobb-Douglas result. All other returns accrue to owners of capital. As noted above, if *n* is large, small differences in the quality of workers (q) can generate large differences in wages and output.

Now we turn to the Foolproof sector. Output in the Foolproof sector is similarly straightforward: It is a diminishing returns sector with labor as the only flexible input–one can think of personal services such as house cleaning, gardening and basic accounting, tasks that demand negligible capital. Subsistence farming would be another example. The key is that workers of different skill levels can be directly aggregated, something that cannot happen in the O-ring sector but which economists routinely do when using conventional Cobb-Douglas production functions (*inter alia*, Hendricks (2002)). In the economic growth literature, such an aggregation often goes under the label of "effective labor." Though this expression is sometimes used to refer to labor-augmenting technical change, it is also used to refer to the aggregate human capital of a population. As Nelson and Phelps (1966, p. 69) put it:

> "[E]ffective labor"… is a weighted sum of the number of workers, the weight assigned to each worker being an increasing function of that worker's educational attainment. This specification assumes that highly educated men are perfect substitutes for less educated men…

This is the assumption we use when modeling the Foolproof sector. In the Foolproof sector, then, two mediocre gardeners can provide as much service as one excellent gardener–something quite untrue in the O-ring sector.

Note that this assumption of perfect substitutability is implicitly employed in growth regressions whenever "average years of schooling" is used as a human capital variable (*inter alia*, Benhabib and Speigel (1994)). Likewise, the U.S. Bureau of Labor Statistics makes the same assumption of perfect substitutability of different skill levels in its Multifactor Productivity Measurement program (Dean and Harper, 1998, p. 26 ff.). There is a rich literature investigating the extent to which workers of different skill levels in fact *are* substitutes for each other. Hendricks (2002), for instance, finds evidence that the elasticity of substitution between skill levels may be five rather than infinity. The current paper contributes to that literature by spelling out a stark case: An economy that combines an O-ring sector where workers with different skills are *never* substitutes in equilibrium, with a Foolproof sector where they are *perfect* substitutes. As we shall see below, this stark example makes it "too easy" to explain cross-country income differences, so there is room for future work that lets the data speak on the question of the actual level of substitutability. The recent work of Jones (2007) points a way toward estimating such substitutability.

Under perfect substitutability, the aggregate effective labor force in the Foolproof sector, $\hat{L}_F$, consists of the number of workers of each skill level multiplied by the skill of that set of workers, added up over all skill levels S. Mathematically,

$$\hat{L}_F = \sum^{S} q_{SF} L_{SF} \qquad (2)$$

As noted above, in the Foolproof sector, output is subject to diminishing returns to labor. For simplicity, but without loss of generality, I assume that the labor share is the same across the two sectors, and I scale Foolproof productivity by A. The non-labor share can be interpreted as return to land or return to (free-entry-driven) entrepreneurs who invent plans to use Foolproof labor; in either event, non-labor income in this sector is distributed lump-sum to the representative consumer. Thus,

$$Y_F = A(\hat{L}_F)^{1-\alpha} \qquad (3)$$

(One could divide this production function by the population size in order to eliminate scale effects, but this would have no noticeable impact on the results below). For workers of a given skill level, the competitive wage (w_{FS}) will equal the marginal product of their class of labor,

$$w_{FS} = (1-\alpha)A(\hat{L}_F)^{-\alpha} q_S$$

The only other conditions are the size of each class of workers. In the benchmark model, I assume only two types of workers: the high-skilled (H) and the unskilled (U). All high-skilled workers work either in the O-ring or the Foolproof sector: throughout, labor is supplied inelastically. Therefore,

$$L_h = L_{ho} + L_{hf}$$

As noted above, in this benchmark model, I assume that there is only one other class of workers, the unskilled. They number L_u, and each has a skill level of q_u. Thus, the total inelastically supplied labor force equals L_h+L_u.

B. The role of capital

As noted above, capital is used in the O-ring sector only—with automobile or computer chip or spinning jenny production being typical examples. Capital is used optimally, with the marginal product of capital equaling the rental rate. For simplicity, I take the rental rate as given and identical across countries. My preferred interpretation of this assumption is to consider this the steady-state of a typical Ramsey or even Solow growth model. Alternatively, one can think of this overall model as being of a small open economy. Any of these assumptions pins down a unique marginal product of capital.

Note that since the O-ring function is a per-firm function, the marginal product of capital is determined via equation (1), not by summing over all firms; again, this follows Kremer (1993). Given the rental rate of capital r, it is straightforward to show that (1) yield an equilibrium capital stock (see Kremer for derivation) of

$$\left(\frac{\alpha q^n nB}{r}\right)^{\frac{1}{1-\alpha}}$$

Since q^n appears in both the equilibrium wage and the equilibrium capital expressions, this means that differences in worker skill across countries will have a multiplier effect through the capital stock. This makes it particularly valuable to have skilled workers working in the O-ring sector rather than in the Foolproof sector.

C. General Equilibrium

The key general equilibrium condition is that if workers of the same skill level are working in both the O-ring and the Foolproof sectors, then the wage across the two sectors must be equal. This is because workers are free to move across firms, so the law of one price must hold. In the benchmark case–which assumes only two skill levels and a relative abundance of high-skilled workers–the unskilled workers will only find employment in the Foolproof sector. Formally, I state the key general equilibrium condition of wage equality across the two sectors:

$$(1\text{-}\alpha)Bk^{\alpha}q_h^{\ n} = (1\text{-}\alpha)A(\hat{L}_F)^{-\alpha}q_h \qquad (4)$$

Since all variables except for $\hat{L}_F$ are exogenous, it is straightforward to solve this for $\hat{L}_F$. Thus, the equilibrium wage condition uniquely pins down the quality-weighted demand for labor in the Foolproof sector: The O-ring wage pins down the demand for Foolproof labor. Who then, exactly, will fill these Foolproof jobs? Briefly, the answer is: All of the unskilled workers plus just enough skilled workers to push the Foolproof wage down to the level of the O-ring wage. The details follow below.

I've assumed that all labor is supplied inelastically, so everyone will work *somewhere*. As long as (4) holds, every single unskilled worker will work in the Foolproof sector, since that's the only place for them to work (In this section, as noted above, I refer to all workers who are below the highest skill level as "unskilled," and denote it by $\hat{L}_{UF}$, and have and identical skill level of q_u. This gives us only two classes of workers, *U* and *H*. Equivalently, one can consider $\hat{L}_{UF}$ to be an undifferentiated mass of less-skilled workers with average skill level of q_u). That means that L_u workers will provide q_uL_u units of effective labor. Once all of these unskilled workers are in the Foolproof sector, then at the margin, high-skilled workers are drawn over from the O-ring sector, each one slightly pushing down the Foolproof wage, until $\hat{L}_F$ units of effective labor are supplied. We denote the number of high-skilled workers demanded by the Foolproof sector by L_{hf}. So L_{hf} high-skilled workers are in the Foolproof sector (each providing q_h units of effective labor), while the remaining L_{ho} workers are in the O-ring sector. Thus, while the high-skilled *wage* in both sectors is pinned down by the O-ring sector, the *number* of O-ring workers is pinned down by the demand for workers in the Foolproof sector. And the Foolproof demand, in turn is driven by the need to push the Foolproof wage down to the O-ring wage.

The key question, then, is whether this equilibrium will hold. It will indeed, as long as the aggregate of unskilled effective labor is weakly less than $\hat{L}_F$. Informally, as long as there are at least a few high-skilled workers working in the Foolproof sector, the general equilibrium condition holds. In this benchmark case, I assume that this condition holds; below, I explore the alternative, which has potentially policy-relevant consequences.

Thus, I solve from the Foolproof sector back to the O-ring sector, assuming throughout that $L_h \geq \hat{L}_F - \hat{L}_{UF} \geq 0$. In this case $\hat{L}_{UF}$ workers earn an equilibrium wage of

$$(1-\alpha)A(\hat{L}_F)^{-\alpha}q_U \qquad (5)$$

Of course, this implies that in equilibrium, the ratio of skilled to unskilled wages is precisely q_h/q_u. Total Foolproof output then equals Y_F, which is uniquely pinned down by the level of aggregate effective Foolproof labor demand.

What of the O-ring sector? As noted before, O-ring firms expand to meet the supply of high-skilled labor, $L_{ho} = L_h - L_{hf}$. The number of firms equals

$$\varphi = L_{ho}/n$$

Since output is proportional to the number of firms, each of which produces according to (1), then $Y_O = Bk^{\alpha}q^n(n\varphi)$, and hence

$$Y_O = Bk^{\alpha} q_h^{n} L_{ho}$$

Aggregate output equals $Y_O + Y_F$, and output per worker equals $(Y_O + Y_F)/(L_h + L_u)$.

Note that while one could add in the representative agent's preferences across goods as part of the general equilibrium setup, this would be inconsequential, since each sector's output is already completely determined by the labor demand in the two sectors. Thus, allocation of output across goods at a point in time is independent of consumer preferences, as long as the preferences allow *some* substitutability across the two types of goods.

II. Discussion and Extension of the benchmark model

A. General Discussion

As noted above, in this O-ring/Foolproof model, the *wage* of skilled labor in both sectors is entirely pinned down by skilled worker productivity in the O-ring sector (i.e., equation 1). Meanwhile, the effective *quantity* of skilled labor demanded is entirely pinned down by the quantity demanded of aggregate labor at the equilibrium skilled wage minus the effective quantity supplied of *unskilled* labor (all of whom will work).

Informally, the skilled labor just fills up the gap between unskilled supply and aggregate Foolproof labor demand. Thus, equilibrium wage and equilibrium quantity are pinned down in two separate markets.

But why won't unskilled labor find its way into the O-ring sector? After all, the promise of increasing returns should lure workers away from the relatively disappointing Foolproof sector, shouldn't it? The answer flows directly from (1), Kremer's O-ring production function. Consider a case where q_h=1 and q_u=0.9. As noted above, if there are only *two* links in the O-ring production chain, and even if I ignore the multiplier effect of capital, two unskilled workers will produce only 0.9^2 = 81% as much as two high-quality workers. In the Foolproof sector by contrast, an unskilled worker will produce 90% as much as a skilled worker, and will earn 90% of the wage of skilled worker (by equation 5)–so of *course* she will stay in the Foolproof sector.

When we look across countries with different skill levels, though, what will we see? In a *country* whose best workers have $q_h = 0.9$, output in the 2-link O-ring sector will (continuing to ignore capital) produce $0.9^2 = 81\%$ as much as in the $q_h=1$ economy. But in the $q_h = 0.9$ economy, many more workers will work in the Foolproof sector.

Why? For two reasons: First, because in the $q_h = 0.9$ economy, the opportunity cost of working in the Foolproof sector is lower than in the $q_h = 1$ economy–the wage is just lower over in the country's O-ring sector. This is because in the $q_h=0.9$ economy, there are no $q_h=1$ workers pinning down a high O-ring wage.

Second, because in the $q_h = 0.9$ economy, both the skilled *and* unskilled workers produce less effective labor than in the $q_h=1$ economy, so it takes more warm bodies to push the Foolproof wage down to the O-ring wage. With more workers in the diminishing-returns Foolproof sector, and fewer in the increasing-returns O-ring sector, productivity falls farther even than in Kremer's original model.

Both channels grow out of the fact that total factor productivity–A and B in the model–is identical across countries. Thus, the very assumption of identical cross-country TFP that is such a *barrier* to explaining cross-country income differences in most models is actually *key* to explaining cross-country income differences in the O-Ring/Foolproof model.

B. An interesting exception: Unskilled workers out of reach of the O-ring.

What happens if there are so many unskilled workers in the economy that equation (4) is violated? What if the Foolproof wage falls below the O-Ring wage? Note that they key assumption of the model, mentioned in the first page of this paper, is that skilled workers move freely and voluntarily between the two sectors, pinning down an identical skilled wage in both sectors. But if unskilled labor (L_u) is so massive that

$$(1-\alpha)Bk^{\alpha}q_h^{\ n} > (1-\alpha)A(q_uL_u)^{-\alpha}q_h \qquad (6)$$

then we are in a new world. If there are only a *few* too many unskilled workers, then all unskilled workers will work in the Foolproof sector. In this case, ratio of wages between skilled and unskilled workers will be greater than q_h/q_u, and the more unskilled workers there are, the greater the gap will be. Socially, there will now be a noticeable difference between the high-skilled and unskilled workers, since they will work in completely different sectors of the economy, with the high-skilled working only in O-ring jobs and the unskilled working only in Foolproof jobs; it will be a "Two Nations" (Hacker, 2003) economy.

C. Unskilled workers pushed to the next rung down the ladder.

But if the number of unskilled workers is vast compared to the Foolproof demand, then something both different and familiar will occur: Unskilled workers will be pushed down to the next "rung" of the O-ring ladder, and the benchmark model's equilibrium condition (4) will hold for unskilled workers rather than for skilled workers.

The only way that unskilled workers will prefer to work in the O-ring sector is if there are so many unskilled workers that they *alone* create so much labor supply that the equilibrium skilled wage is pushed *far* below the O-ring wage. To reuse the simple capital-free example from section IIA, assuming q_U=0.9q_H and a two-link production chain, then if the supply of unskilled labor is so large that the unskilled wage falls dramatically, then the unskilled workers will be drawn into the O-ring sector, working at 81% of the skilled wage. In such a case,

$$(1-\alpha)Bk^{\alpha}q_u^{\,n} = (1-\alpha)A(q_uL_u)^{-\alpha}q_u.$$

In this case, the unskilled workers would be in the same position as the skilled workers in the benchmark model: They would freely move between the two sectors in order to keep the wage in equilibrium.

In principle, this could lead to interesting discontinuities in the labor market: If there are only a few unskilled laborers in an economy, these workers would all work in the simple Foolproof sector along with a few skilled workers; if there are a moderate amount of unskilled workers, they would work in a "Two Nations" condition, earning wages well below that of their skilled counterparts. But if there were a vast numbers of unskilled workers, some of them would work in a familiar O-ring sector that was one rung down on the economic ladder. Thus, this image presents itself: The O-ring sectors as rungs on an economic ladder, with the Foolproof sector as the spaces between the rungs (Figure 4).

In Kremer's original model, the rungs on the ladder were the only places for workers to reside, so small differences in skill would necessarily cause large differences in wages and aggregate output *within* a given country. But this is not what we typically see in wage regressions: Instead, as noted in the introduction, worker skills like math scores and IQ have only modest impacts on individual wages. But in the O-Ring/Foolproof model, the vacuum between the rungs on the ladder is filled by a routine diminishing returns sector, where small differences in skill indeed lead to small differences in wages and productivity, just as we typically see in the data.

At the same time, the O-Ring/Foolproof model could explain why in some of the world's immigrant-heavy rich countries, with large numbers of new, unskilled workers, income inequality has recently increased: Large numbers of less-skilled workers could be pushing

Foolproof-sector skilled wages down below the equilibrium condition of (4), thus either putting unskilled workers "below the rung" or even "down to the next rung" on the economic ladder. In either case, the ratio of skilled and unskilled wages would differ by a factor of more than the q_h/q_u implied by the benchmark model.

If this were the case, we would expect to see skilled workers devoted completely to O-ring jobs. Further, we would see unskilled workers devoted either to Foolproof-type jobs or O-ring jobs of much lower productivity–clear testable implications of the model. But in the benchmark case, which assumes *either* a low supply of or a high demand for unskilled Foolproof workers, no such "multiple ladder-rung" effect exists: All workers in the economy work at a wage that is closely tied to the wages in the skilled workers' O-ring sector.

D. Econometric implications.

Two key empirical results the flow from the benchmark model, which simply adds a diminishing returns "dual labor market" (*inter alia*, Dickens and Lang, 1985) to the O-ring model of Kremer:

1. When a labor econometrician estimates Mincer-style (1974) wage regressions within a given country whose data are generated by the benchmark model (i.e., one with a relatively high ratio of skilled to unskilled labor), she will find that the wage is precisely proportional to q, the skill of the worker. This is because the only variation in wages she will find will be across workers in the Foolproof sector, a sector that behaves in a conventional, diminishing returns manner.

2. When a macroeconometrician estimates cross-country productivity regressions across countries whose data are generated by this model, she will find a completely different result:

Productivity differences for countries with different levels of q_H will be vast–*indeed, they will be even larger than in Kremer's O-ring model*.

In Kremer's benchmark model, productivity per worker equaled $Bk^{\alpha}q^{n}$, but in the benchmark O-ring/Foolproof model, the gap is much larger. This is because the O-ring sector is an increasing returns sector, one filled with positive productivity spillovers–something inherent in the use of the term "strategic complementarity." Each high-skilled worker who is lured into the Foolproof sector reduces aggregate productivity dramatically (Strictly speaking, the first few Foolproof workers are extremely productive due to diminishing returns, but this high-average productivity range is relatively modest in size). Holding A and B constant (the exogenous O-ring/Foolproof productivity parameters, respectively), this means this means that a fall in a nation's high quality skill level, q_h, drives O-ring wages down dramatically which makes the Foolproof sector all the more appealing as a place to work which in turn lures even more workers out of the O-ring sector. This can cause a dramatic relative decline in that nation's GDP per worker, even for small declines in a nation's q_h.

III. A quantitative example

Figure 3 gives an idea of how this model can easily generate differences in living standards that are on the order of 30X between the world's richest and poorest countries, while simultaneously implying only small intra-country wage inequality. In this simulation, A=B=100, L_h = 1,000,000, L_u=100,000, and within a given country, $q_u = 0.9q_h$. I chose r=4% to match the conventional interest rate used in dynamic general equilibrium models.

Lynn and Vanhanen (2002, 2006), along with a variety of other IQ researchers (*inter alia*, Jensen (1998)), find that the world's poorest countries have populations whose average IQ's are two standard deviations below those in the richest countries, equivalent to 30 IQ points. Much of this is almost surely driven by differences in environment, and ongoing research is addressing the important questions both of how to improve mental ability in the world's poorest countries as well as how much, if any, of these cross-country differences are genetic in origin.

Since 1 IQ point predicts about 1% higher wages within a country (see Jones and Schneider, forthcoming, and citations within, especially Zax and Rees (2002)), I take a 1% change in q to be equivalent to a 1 point difference in IQ. Thus, by looking at a range of q=0.7 for poor countries to q=1.0 in rich countries, we can roughly capture the range of IQ differences around the world. I should note that in fact, the IQ differences between the 5th and 95th percentiles of the national average IQ distribution actually range from 68 to 106, for a range of 38 points, with East Asian countries representing the top of the range of national average IQ.

Of course, one might question whether this distribution of labor supply–with 90% in the "high" skill level and 10% in the "low," but a more realistic distribution of labor supply could readily generate the same qualitative results: The key is that a substantial fraction of workers in the world's richest countries must be high-skilled O-ring workers in equilibrium. Such workers might all work on one rung of the O-ring ladder, while below that level, demand for Foolproof labor might be sufficient to employ the rest.

It is straightforward to use equation (4) along with the O-Ring and Foolproof production functions, plus the supply of labor, to uniquely determine the aggregate outcome–at this point, it is a matter that can be resolved in an Excel spreadsheet (available on my website). Figure 3 and Table 1 present the results. This example illustrates a point made in section IIC: In this quantitative example, the O-ring sector in the q=1 country is only 6 times more productive than in the q=0.7 country, yet GDP per capita is 32 times more productive in the q=1 country. Why? Because in the q=0.7 country, more and more skilled workers are drawn into the less-productive

Foolproof sector. Within this model, a q=0.7 worker living in the q=0.7 country would earn only 3% as much as her identical twin living in the q=1 country. This model thus easily replicates the vast living standards that exist across countries without assuming vast differences in *people* across countries.

IV Implications

I now turn to a few implications and possible extensions of this framework.

1. *Low-skilled immigrants don't hurt natives.* Consider the benchmark version of this model, where only one O-ring rung is occupied, and where a mixture of high- and low-skilled native workers are employed in the Foolproof sector. If a few low-skilled immigrant workers arrive, what is the macroeconomic impact? The answer is clear: a smaller number of high-skilled natives will move back into the increasing-returns O-ring sector, and the new low-skill workers enter the Foolproof sector. But since wages for high-skilled workers *in both sectors* are pinned down by the O-ring production function, there is no impact on high-skilled native wages. This is close to the stereotypical case of "immigrants taking the jobs that natives don't want." The net result is a wash for both high-skilled and low-skilled wages.

If there are massive amounts of low-skilled immigration, then we are in the world of IIB or IIC; high numbers of low-skilled immigrants may lower the wages of low-skilled native workers, by pushing them "between rungs" or even down to the next O-ring rung. But low-skilled immigrants have no impact at all on the wages or productivity of high-skilled workers. This appears to match the stylized fact that in the U.S., low-skilled immigrants appear to do no measurable damage to the wages of high-skilled natives, but may hurt the wages of low-skilled natives (Tabarrok and Theroux, 2006).

2. *Border areas as regions of Foolproofness*. The O-ring/Foolproof framework focuses attention on cases where workers of varying skill levels are substitutes in the *same country's* Foolproof production function. But workers in a low-skill country employed near the border of a high-skilled country may, in fact, serve as substitutes within the high-skilled country's Foolproof production function. Thus, rather than having their wage pinned down by their home-country's low-productivity O-ring function, they may have their wage pinned down by the neighboring country's high-productivity O-ring function. Earning 90% of the high-skill country's wage will certainly be much better than earning 100% of the low-skill country's wage. Being able to substitute for the high-skilled country's Foolproof workers would be the key to higher wages for the low-skilled country's citizens. The O-ring/Foolproof framework emphasizes that in border regions we should look for workers switching away from forms of production where strategic complementaries are important toward forms of production where workers of various skill levels can be aggregated. Of course, if Friedman (2005) is correct in claiming that technological progress is dramatically lowering barriers to the international production of goods and services, then any place on earth could conceivably become a "border region." If the whole world becomes part of the border region of the world's most productive economies, this could raise productivity and living standards in the world's poorest countries according to the model presented here.

4. There can be only one Foolproof Sector in each economy; and it's at the bottom. The model has a clear prediction that workers of different skill levels will only substitute for each other in the lowest-skilled sector of the economy. Thus, we will not find many low-skilled attorneys combining their efforts to arrange a merger between two Fortune 100 firms. But we may find one Harvard Law graduate working in a medium-sized rural town single-handedly taking about

1/3 of the cases, while a dozen lawyers from less prestigious schools share the rest of that town's legal business. Bundles of the lowest-skilled workers will only be seen in the least-productive parts of the economy, while higher-skill workers may be in both O-ring and Foolproof jobs. This O-ring/Foolproof dichotomy may help economists clarify the distinction between primary and secondary labor markets (Reich et al., 1973); firms using an O-ring production function would want to carefully screen job candidates, while workers of various skill levels might be lumped together in Foolproof jobs indiscriminately.

5. These results generalize to continuous skills; but there's still only one Foolproof sector, and it's at the bottom. I omit this proof from the paper. Thus far, I've assumed that worker skills are distributed discretely–with gaps between high- and low-skilled workers leading to gaps in the rungs of the economic ladder.

Instead, consider continuously distributed skills. In this case, think of the economy's O-ring jobs as being distributed from the top down: Start with the highest-skilled workers and move downward from there. All workers not in an O-ring sector at a given point end up in the Foolproof sector. If skills are distributed continuously, then whenever the number of workers in the Foolproof sector would be sufficient to make equation (6) true–that is, the Foolproof wage is lower than the O-ring wage–then a new O-ring sector is created for the next lowest skill level. If skills are distributed continuously, then O-ring sectors are also distributed continuously, until equation (4) holds. At this point all remaining workers–who will encompass a variety of skill levels–will work in the foolproof sector.

So if skills are distributed continuously, then there will be no "gaps" between the rungs. Instead, there will be a continuous gradation of O-ring sectors at the top of the economy, but at the bottom there will be a single Foolproof sector that employs an amalgamation of workers of all skill levels. This will include some mixture of the lowest level of O-ring workers with workers of all lower skill levels. The effective labor of these workers will be combined together via an integral counterpart to the summation equation (2).

This implies that Kremer's original O-ring model is a special case of this model: If there are vast supplies or workers of every conceivable skill level, the econometrician will observe vast intra-country inequality, since most workers will be in O-ring sectors with different skill levels. A uniform-type skill distribution would yield this kind of result, and would imply that intra-country returns to skill would be the same as inter-country returns to skill. In this world, the Foolproof sector might appear negligible.

Instead, if there is less skill inequality–something more like a Normal distribution–then the vast numbers of workers would work in a set of O-ring sectors covering a small region of the skill space, with the rest of the workers together in the Foolproof sector. So the distribution of intra-country skills will determine whether the econometrician sees a world like Kremer's or a world like the benchmark case presented in section I.

6. The model poses a stark case; but empirical work can sort out "degrees of O-ringness" and "degrees of Foolproofness." Jones (2007) tackles the empirical question of how much strategic complementarity is enough to explain real-world income differences; applying his methods to this model would be a natural extension.

7. What this tells us about education. In empirical growth research, the coefficients on education are rarely large (*inter alia*, Bils and Klenow (2001), and citations therein), and the evidence for large external returns to human capital is modest (Moretti, 2004). At the same time, Hanushek and Kimko (2000) and Jones and Schneider (forthcoming) found that math, science, and IQ-test skills all appear to have larger payoffs for countries than for individual workers. Thus the elements of jobs that fit along the "O-ring/Foolproof" axis are likely to be the elements that use the skills measured in math, science, and intelligence tests, not the skills inculcated in raw schooling. This may mean that general education doesn't raise the skills that help people work in O-ring sectors: Future research can investigate whether math and science courses raise O-ring productivity, while reading and social science courses only raise productivity in the Foolproof elements of modern jobs.

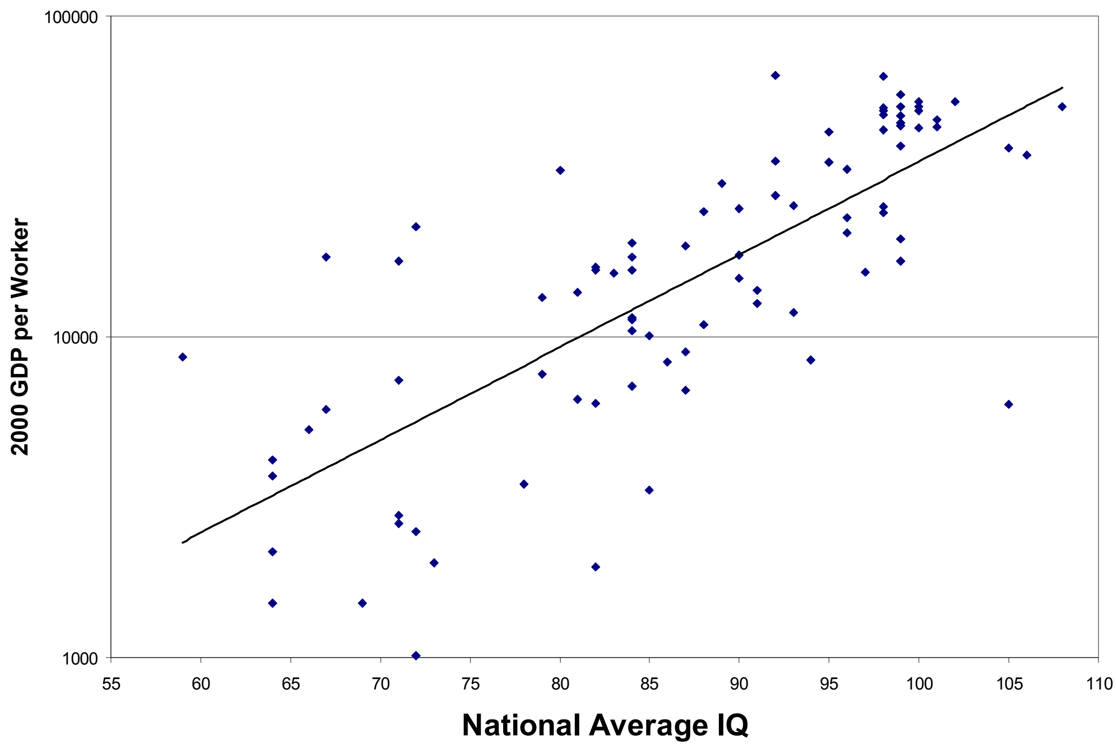
8. A naïve prediction. According to the O-ring/Foolproof model, the very highest elites are likely to earn the same across countries, since they will have access to identical production functions (assuming elites have the same skill level across countries). So if we compare perhaps the top 1% of citizens within each country to the top 1% in every other country, we should expect to see low levels of inequality. It is in the lower O-ring rungs and in each country's Foolproof sector that we should expect to see massive inequality. The pair of production functions employed in this paper can explain why barbers earn more in the Britain than in India, while corporate executives in Britain and India live quite similar lives.

V. Conclusion

This paper builds on an insight latent within Kremer's (1993) O-ring theory of economic development: Within a given country, when two groups of O-ring workers differ in their skill by a factor of ε, their equilibrium wages will differ by a factor on the order of $n\varepsilon$, where n is the number of links in the O-ring production chain. That means that if *any* other production process is available within the country that would create a pay gap of less than $n\varepsilon$, that alternative production process could readily hire the slightly-less-skilled workers. Thus, slightly-less-skilled workers would leave the O-ring sector and move to the alternative sector. Since such labor mobility is easy within countries but difficult across countries, an econometrician will readily find evidence of large returns to skill across countries but small returns to skill within countries.

In this paper, I've used a conventional diminishing returns to labor sector as one example of a non-O-ring sector, but other production processes would surely generate the same outcome. Any production function that fills the space between the "$n\varepsilon$ gaps" or the "rungs on the O-ring ladder" would do the job. If there is more than one kind of job–and surely there is–then this model may prove useful in explaining how differences in "labor quality" (Hanushek and Kimko, 2002) can matter very little for individuals while still mattering massively for entire nations.

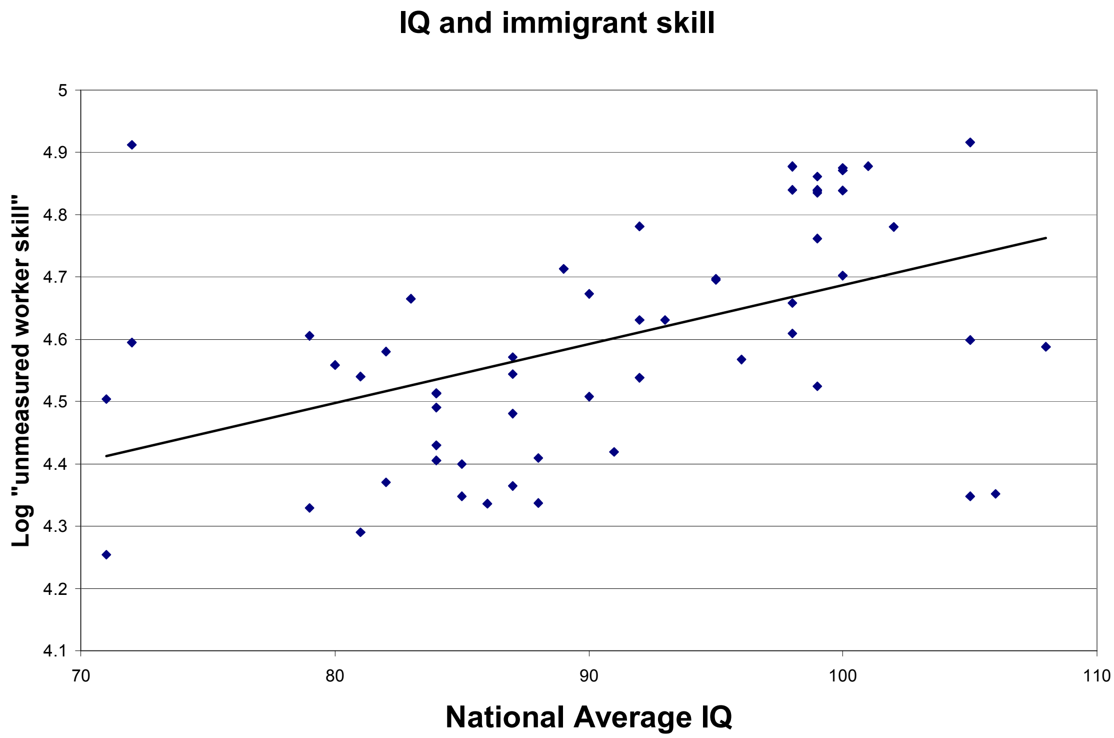
**Figure 1: National Average IQ (Lynn & Vanhanen, 2006)
and Year 2000 GDP Per Worker**



Notes: Y-axis shows GDP per worker in logarithmic scale. In this bivariate regression, the coefficient on national average IQ is 0.067, and the R^2 is 58%. Thus, a one-point rise in IQ is associated with 6.7% higher output per worker. The sample covers 87 countries. The outlier in the lower-right corner is China (IQ=105).

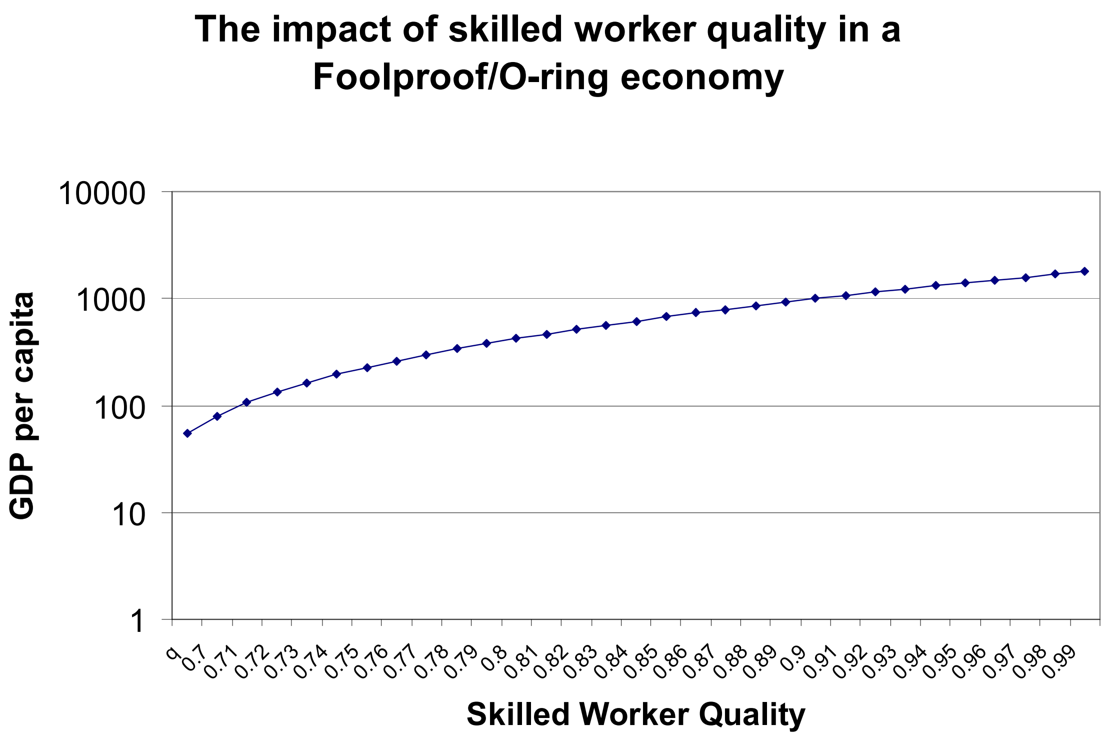
Source: Lynn and Vanhanen (2002) and Penn World Tables 6.1 for IQ and GDP data, respectively.

Figure 2



Notes: The x-axis reports estimates for national average IQ for country *i* from Lynn and Vanhanen (2006). The y-axis reports values for uws_i, the unmeasured worker skill estimate for immigrants from country *i,* as estimated in Hendricks (2002). uws_i is the log average wage of immigrants for country *i,* adjusting for age and education. The trendline reflects the OLS coefficient of 0.95 reported in the text, and the R^2 is 22%.

Figure 3



Notes: The x-axis is the quality of skilled workers in a benchmark O-ring/Foolproof economy, and the y-axis is GDP per capita in that model economy. Thus, the value above 0.7 is the output in such an economy if the high-skilled workers had a skill level of 0.7. Unskilled workers in a given country are always assumed to have a skill level 90% that of a skilled workers in that country. The supply of unskilled workers is $1/10^{th}$ that of skilled workers, A=B=100, and n=3.8. Holding the other values constant, a value of 3.8 was chosen to generate an outcome where GDP per capita was 32X higher in the q=1.0 economy compared to the q=0.7 economy.

Figure 4
The Ladder: O-Ring Sectors as rungs,
Foolproof Sectors as gaps between rungs

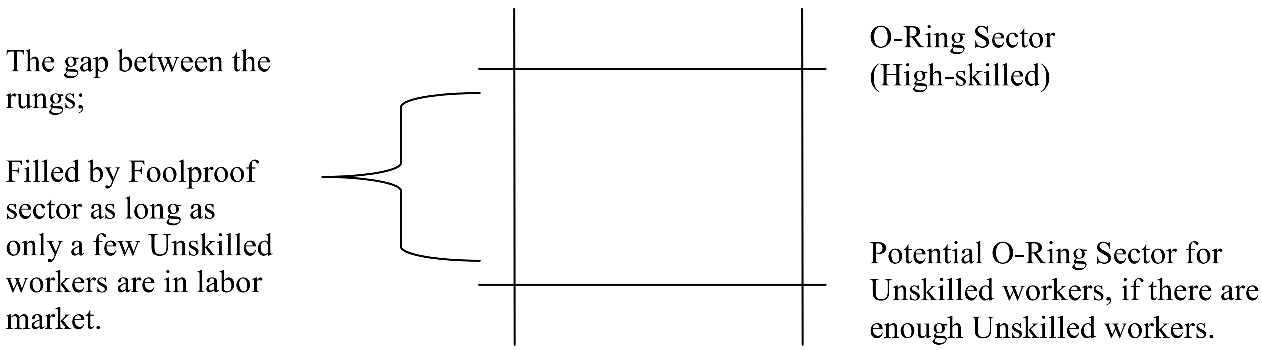


Table 1
O-Ring/Foolproof Simulation

Skilled-worker quality	Number of links	O-Ring wage	Effective Labor	Skilled Labor	O-Ring Workers	O-Ring Output	Foolproof Output	GDP per capita
0.7	3.8	235	644,078	1,000,000	169,889	59,562,754	614,051	55
0.75	3.8	333	495,088	1,000,000	429,883	213,596,152	539,173	195
0.8	3.8	461	387,082	1,000,000	606,148	417,329,186	477,417	380
0.85	3.8	627	307,189	1,000,000	728,602	681,485,980	425,865	620
0.9	3.8	837	247,029	1,000,000	815,523	1,018,267,028	382,370	926
0.95	3.8	1,099	201,006	1,000,000	878,415	1,441,445,373	345,323	1,311
0.99	3.8	1,354	171,755	1,000,000	916,510	1,852,512,766	319,495	1,684
1	3.8	1,425	165,297	1,000,000	924,703	1,966,463,320	313,500	1,788

Notes: Unskilled workers in a given country are always assumed to have a skill level 90% that of a skilled workers in that country. The supply of unskilled workers is 1/10th that of skilled workers, and drawing on equation (4), A=B=100, and n=3.8. Effective labor equals number of workers weighted by worker quality. Holding the other values constant, a value of 3.8 was chosen to generate an outcome where GDP per capita was 32X higher in the q=1.0 economy compared to the q=0.7 economy. Note that O-Ring sector wages differ only by a factor of 6, a point explained in IIC.

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