



## Population Genetics and Economic Growth

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**Synopsis:** This paper builds an age-structured model of human population genetics in which explicit individual choices drive the dynamics via sexual selection. In the model, agents are endowed with a high-dimensional genome that determines their cognitive and physical characteristics. Young adults optimally search for a marriage partner, work for firms, consume goods, save for old age and, if married, decide how many children to have. In accord with the fundamental genetic operators, children receive genes from their parents. An agent's human capital (productivity) is an aggregate of the received genetic endowment and environmental influences so that the population of agents and the economy co-evolve. After calibrating the model, we examine the impact of physical, social, and economic institutions on population growth and economic performance. We find that institutional factors significantly impact economic performance by affecting marriage, family size, and the intergenerational transmission of genes. The principal novel findings are that i) genetic diversity has a nonmonotone causal impact on population size and economic performance; ii) an endogenous population threshold exists which, absent frictions, causes societies with declining populations and output to reverse course and grow; and iii) that the emotion love substantially accelerates economic growth by increasing genetic diversity 'just enough', which we term '*The Goldilocks Principle*'.

**Key words:** growth, population biology, genetics, evolution, fertility, marriage, psychology

**JEL classification:** J12, J13, J24, O40

### 1. Introduction

For its implications throughout biology and the social sciences, no subject is intellectually more interesting [than the co-evolution of genes and environment].

(Edward O. Wilson, *Consilience*, 1998, p. 137)

It is well accepted that human capital is the source of long-run growth, as human capital engenders technological innovation (Lucas 1988, Romer 1990). This paper provides a biological foundation for the production of human capital by modeling the production of humans. Behavioral geneticists have shown that one's genetic endowment and early childhood experiences are the fundamental factors that beget adult cognitive skills (McClearn et al. 1997, Plomin & Petrill 1997, Plomin 1994). As a result, the way that

individuals meet and mate, and the post-mating household structure, fundamentally determine adult productivity. Put more simply, we follow Becker (1993) by modeling the nature *and* nurture constituents of human capital.

In this paper we seek to take nature and nurture seriously. We do this by endowing each agent in the model with a high-dimensional genome which is derived from the primary genetic operators acting on his or her parents' genes: recombination, linkage, and mutation. An agent's genome codes for baseline cognitive ability, physical appearance, and gender. To characterize where an individual's genetic material comes from, adults make two-sided marriage decisions, and, if married, choose how many children to have. Sexual selection occurs as some individuals are unable to find a mate with whom to reproduce. Indeed, this is a model of human sexual selection which is mapped into economic output via the intergenerational transmission of human capital.

Because the model includes the search for a marriage partner, we use findings from evolutionary psychology to identify the factors that lead individuals to marry, including a spouse's human capital, physical attractiveness, the ability to effect reproduction, and the value of companionship. In this way, the model seeks to integrate the biology and psychology of human mating and reproduction with the economic and social environments in which individuals find themselves. The model is therefore an exercise in population genetics (Ginzberg 1983, Emlen 1984, Keyfitz 1984, Little & Haas 1989, Takahata & Clark 1993), but departs from the biological literature by modeling the (boundedly) rational decision-making unique to humans. Such a research program has been advocated by E. O. Wilson (1984), who stated during a conference in 1981 that 'The optimization technique is, I think, very valuable for micro-evolutionary analyses, particularly when one [has] a thorough knowledge of the species and of its adaptive repertoires... Behavior and genetic distribution are then optimized over a small portion of the conceivable adaptive landscape.'

In terms of economic choices, viz. consumption and production, an agent's genetic endowment acts as a constraint on individual choices. For example, education raises an agent's human capital and labor income, but does so only given one's genetic endowment. As a result, genetics constrains achievable consumption, savings, and the ability to find a marriage partner. These in turn affect the economic landscape in the following generation. The population of agents and the economy therefore co-evolve.

Considering genetics and family structure as the building blocks of human capital stands in contrast with the literature that models human capital as purely education or experience with or without financing constraints (Lucas 1988, 1993, Stokey 1996, Galor & Zeira 1993, Galor & Tsiddon 1997a, b). Rather, the model in this paper is grounded in behavioral genetics (see Zak 2000), extending the analysis of human capital to the level of the genome. The model is driven by marriage and fertility, and thus is related to the seminal analysis of fertility decisions by Becker & Tomes (1976), and subsequent work by Becker & Barro (1988), Becker et al. (1990), and Tamura (1996), as well as the literature on marriage matching (Becker 1973, 1974, Lam 1988, Burdett & Coles 1997, Weiss 1997). The primary point of departure of this paper is the inclusion of explicit biological factors for mating and reproduction that underpin the creation of human capital.

The model is solved numerically and calibrated to match physiologic and U.S. demographic data. Once the model is calibrated, we examine a number of environmental and institutional changes that impact marriage and reproduction, including inequality in income and genetic attributes, the transition to an information economy, population bottlenecks, endogamy, and love. We show that marriage and fertility decisions affect the economy's growth rate via the transmission of human capital from parents to children, and that the environment and institutions that impact these choices cause substantial variations in economic performance.

The principal findings of this paper are that (i) sustained population and economic growth is more likely with sufficient genetic diversity, but too much diversity may negatively impact growth by reducing marriage opportunities; (ii) there exists an endogenous repelling threshold such that if population size shrinks sufficiently, marriage matching optimized to the environment leads to an increased marriage rate leading to a population rebound and economic revitalization; and (iii) including the emotion love in the model substantially accelerates population and economic growth by increasing the degree of genetic diversity 'just enough'. We call this latter result 'The Goldilocks Principle'. It reveals an additional important role for the emotions in economic analysis following Hirshleifer (1987) and Frank (1988). Importantly, these results obtain without the assumption that genetic diversity is itself valuable; indeed, the model's results obtain purely through sexual, rather than natural, selection, so the a priori impact of genetic diversity is ambiguous. Sexual selection has arguably a much greater impact on the distributional dynamics of genes than does natural selection, particularly in modern societies (Miller 2000).

## 2. Theory

In this section we present a behavioral theory of economic growth in which individuals are heterogeneous over many dimensions: age, the expression of genes, marital status, gender, income, and the number of siblings. Let the index  $i \in \mathbf{R}^+$  identify individuals by all traits in which they vary from one another, with each agent having a unique index. The model has a large number of agents who live three periods in overlapping generations.<sup>1</sup> The first period of life is childhood (period 0), the second period is young adulthood (period 1), and the third period is old age (period 2). Following the standard economic approach, agents in this model maximize the lifetime utility derived from a variety of activities—consuming goods, being married, and having children—rather than maximizing, for example, reproductive fitness.<sup>2</sup> We show below that biological and psychological factors directly impact utility maximizing decisions so that fitness and utility are closely related.

Because our purpose is to endogenize the production of human capital by focusing on biological and environmental influences impacting marriage and fertility decisions, in the following subsections we characterize marriage and reproduction choices separately before presenting the full model that, in addition to these, includes choices for family size, consumption, and savings.

### 2.1 *Finding a marriage partner*

The first task that agents execute upon passing from childhood to young adulthood is to search for a marriage partner. In each matching round, two individuals meet at random and, if they are of the opposite sex, evaluate each other regarding suitability for marriage. That is, this is a two-sided matching problem.<sup>3</sup> Note that the marriage market is competitive. Buss (1994, p. 144) notes that 'People with higher desirability have more resources to offer and so can attract a mate with a higher value. Those with low value must settle for less.' To wit, when one marries one foregoes unions with other potential marriage partners incurring an opportunity cost.

In the marriage market, an agent knows his or her own attributes, with a potential mate's attributes observable upon meeting. Agents also know the distribution of types of potential spouses when the marriage market opens. Agents who marry as young adults stay married through old age; agents do not die young, and divorce is not part of the model.<sup>4</sup> Because siblings who are raised together almost never copulate due to a biologically-based sexual aversion to each other known as the Westermarck effect, we rule out marriage between siblings who meet during the matching game.<sup>5</sup>

Marriage confers several benefits to individuals. First, as young adults of both sexes work in this model, marriage raises household income, though we make no distinction between market and nonmarket work as in Becker (1973).<sup>6</sup> Because labor income increases in human capital, a spouse with more human capital is desirable for the income he or she brings into the household. We ignore intrahousehold bargaining as in Lundberg & Pollak (1993, 1996) and Greenwood et al. (1999) as the spousal division of income does not affect the model's results. Instead, we model household income and costs as being equally shared by both partners, using a variant of the Samuelson (1956) household consensus model. Equal sharing by spouses means that a married individual's consumption of goods may be less than consumption when single if one's spouse's human capital is less than one's own. Marriage still occurs between individuals of different human capital levels because there are several other utility flows from marriage besides the consumption of goods.

In addition to bringing in income, a marriage partner also enables reproduction. All agents in the model have preferences for children which captures the genetically programmed desire to reproduce. We ignore organic infertility in the model, though some individuals are infertile because they are unable to find a suitable spouse. Further, reproduction only occurs within marriage.<sup>7</sup> Married individuals also receive a pure utility flow from the act of being married, which we call the 'joy of marriage.' The joy of marriage can be understood as the utility from companionship, sex, or any of the other benefits that individuals receive from being married (Regan & Berschied 1997).

The literature in evolutionary psychology identifies two primary factors that consistently determine a mate's desirability across time and cultures: earnings ability and physical attractiveness (Buss 1989, 1994, Buss et al. 1990, Buss & Barnes 1986). Following Burdett & Coles (1997), we call an individual's desirability on the marriage market his or her *pizzazz*. Because women invest more biological resources in their offspring than men, e.g. pregnancy, lactation, etc., over millennia women evolved to be

highly sensitive to the availability of resources when choosing a mate (Trivers 1972, Seger & Trivers 1986). Historically, if a woman became pregnant by a man with few resources, both she and her child were unlikely to survive the rigors of pregnancy and post-partum childcare. Men, on the other hand, are able to limit their investment of resources in children at procreation, but must select sexual partners who have the ability to produce viable offspring. As a result, over evolutionary time genetically successful men have focused on cues of a woman's health as an indicator of her desirability, i.e. her ability to bear and raise children to reproductive maturity. Standards of beauty have evolved to correspond to indicators of health and youthfulness, including smooth skin, large eyes, body symmetry, small waist to hip ratio, full lips, and shiny hair. (Johnston & Franklin 1993, Buss 1994.) Women similarly evaluate a man physically as an indicator of the quality of his genes (Miller 2000). We will use the shorthand beauty to denote physical appearance in both men and women.

The differential investments by men and women in reproduction causes the evaluation of a mate's pizzazz to be asymmetric. The male-female asymmetry for mate selection preferences has been borne out in an exhaustive study of 37 cultures in 33 countries by Buss et al. (1989). Following directly from these evolutionarily-driven findings, the pizzazz of agent  $i$ ,  $p^i$ , as evaluated by a potential spouse is a weighted sum of his or her human capital  $h^i$ , and beauty,  $Y^i$ ,

$$p^i = \eta_q h^i + (1 - \eta_q) Y^i, \quad (1)$$

where the weight  $\eta_q$  placed on each attribute varies across sexes  $q = m, f$ . The utility flow from the joy of marriage is increasing in one's mate's pizzazz as in Burdett & Coles (1997) since a higher pizzazz mate is more highly valued for both biological and economic reasons.<sup>8</sup>

In sum, there are four factors that affect the marriage matching decision: random meetings, beauty, human capital, and reproduction. These factors are included in the model for two reasons. First, the available evidence indicates that these factors significantly and universally affect individuals' marriage decisions.<sup>9</sup> Second, the degree of assortative mating of marriage partners with respect to human capital alone is low (Regalia & Rios-Rull 1999). Including psychological mating criteria in the model generates asymmetries in mating, though positive assortative mating vis-à-vis pizzazz continues to obtain as we show in Section 3. Further, searching for the best available marriage partner provides one's children with the best possible genes when they enter the marriage market; that is, this strategy is akin to maximizing reproductive fitness.

## 2.2. Genetics and human capital

The primary motivation for endowing each agent with a genome follows from recent work in behavioral genetics showing that a significant proportion of one's cognitive ability is inherited. Genetic factors that contribute to cognitive ability include short- and long-term memory, the ability to learn new information, awareness of social cues,

decision-making aptitude, and language skills. McClearn et al. (1997) estimate, by studying adult twins, that 62% of cognitive ability is due to genetics. Plomin & Petrill (1997) and Hamer & Copeland (1998, chapter 6) survey a large number of studies of twins, siblings, and adopted children that use a variety of analytical techniques and report that the heritable proportion of intelligence is estimated between 48% and 75%.<sup>10</sup> In related work, Behrman & Taubman (1989) find that 81% of educational attainment is due to genetics.

These studies indicate that formal education only accounts for about one-quarter of one's abilities. This occurs because highly educated members of society self-select to obtain more education as they are endowed with the ability to do so (Behrman et al. 1994, Ashenfelter & Rouse 1998, Rubinstein & Tsiddon 1999). Self-selection by innate ability also occurs when workers choose particular types of jobs (Bartel & Sicherman 1999). Plomin & Bergeman (1991) call self-selection of particular environments directed by one's innate abilities 'the nature of nurture'. Thus, human capital has a significant innate component.

In addition to genetics, family environment plays an important role in the development of human capital. Parents transmit social and cultural information, called 'memes' by Dawkins (1976), to their children. Indeed, humans are distinct among primates in the length of their childhood, which is related to the time required for parents to teach children complex skills (Weiss & Mann 1985). Household environment accounts for between 11% and 25% of the variance of cognitive ability in estimates by McClearn et al. (1997), and Plomin & Petrill (1997), respectively. Because per child parental nurturing is affected by the number of children in a family, as family size increases beyond two each child's average educational attainment falls (Behrman & Taubman 1989) as do grades in school (Downey 1995). This effect obtains even after controlling for parents' income, education, and other family attributes. Interestingly, children's outcomes are better when there are two children in a family, rather than only one. Children without siblings receive maximal parental nurturing, but less child-to-child nurturing, reducing their acquisition of human capital relative to children in two-child families. Thus, parents have two effects on their children's human capital, the genetic endowment they provide them with at conception, and the familial nurturing that stimulates or inhibits the expression of genetic abilities.

An individual's genome is represented by a 52 dimensional vector,  $A$ , with the first fifty dimensions corresponding to the genes for cognitive ability, the 51<sup>st</sup> determining gender, and the 52<sup>nd</sup> coding for beauty. The on-off nature of genes is captured by representing the genes that code for cognitive ability and gender as taking values of either one or zero. That is, because the particular genes that code for cognitive ability are at present unknown, as well as for computational convenience, in the model we equate genotype and phenotype.<sup>11</sup> Further, the genes for cognitive ability are ordered so that the most important factor,  $a_1$ , is first, and the second most important,  $a_2$ , is second, etc. Though this ignores the importance of combinations of genetic factors in the generation of innate ability, it is a useful construct when comparing ability across individuals. Lastly, the genetic factors that produce beauty are compressed into a scalar,  $Y^i \in (0,1)$ . Using 52 genes in agents' genomes allows genetic operators (discussed

below) to produce sufficient heterogeneity among individuals while at the same time ignoring DNA that does not appear to code for proteins or is redundant. Such 'junk DNA' makes up 97% of the human genome.<sup>12</sup> More practically, a 52 dimension genome balances the genetic diversity required for nontrivial results with a reasonable computational time needed to solve each version of the model.<sup>13</sup>

When the society under study begins, the genetic endowment for the initial population of Adams and Eves is generated by a random draw at each location on the genome. After the initial generation, when individuals meet, marry, and reproduce, the genome of each child is determined by the fundamental genetic operators, *recombination*, *linkage*, and *mutation*, acting on his or her parents' genomes. Recombination (also called crossover) is the primary method through which a child's genetic material is produced from his or her parents' DNA. Classical Medelian genetic analysis shows that the contribution of the mother's and father's genes produces one of two possible phenotypic outcomes. Suppose at a particular location the mother has the allele  $Aa$ , where as is standard,  $A$  denotes a dominant trait and  $a$  a recessive trait, and the father is an  $aa$ . That is, the mother is heterozygous and the father is homozygous in this gene. Then, the child has a one in two chance of being  $Aa$ , and an equal chance of being  $aa$ .

Because of the difficulty in assigning dominance and recessiveness to traits as complicated as those that code for cognition, we adopt a simplified method for recombination that simply identifies the *expression* of each trait as 'on' or 'off'. When genetic material is represented by zeros and ones, irrespective of dominance or recessiveness, if a child receives (0,0) from his or her parents, the expression of this trait will be 'off', while if he or she receives (1,1), the trait is 'on'. The only difficulty occurs for heterozygosity, (0,1) or (1,0). In this case, we simply randomize to determine which trait is expressed, i.e. either a 1 or 0.<sup>14</sup> By doing this, we can reduce an agent's genome to a vector of zeros and ones that represent the expression of each trait. A generic genetic code for an individual is

[0, 1, 1, 0, 1, 1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 1, 0, 0, 0, 0, 1, 1, 0, 1, 1, 0, 0, 1, 0, 1, 0, 0, 1, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 1, 1, 0, 1, 1, 0, 0, 1, 0, 0, 1, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0.456].

In this example, the first fifty columns of the genome vector code for the expression of genes that determine innate ability, the 51<sup>st</sup> column is one's sex (0 denotes female; 1 denotes male), and the 52<sup>nd</sup> codes for the agent's beauty, in this case, 0.456.

The second genetic operator is linkage. Linkage binds the alleles of adjacent genes together so that they always occur as a pair. Because recombination is the primary way that genetic material is distributed from parents to offspring, linkage has a small effect on population genetics (Strickberger 1985). Further, the extent of linkage for any two adjacent genes is, at the present time, an open question. As a result, we include this operator by linking genes 10 and 11, which would imply that roughly 1,150 genes are linked for an average human being.

The final genetic operator is mutation. For each gene, after recombination and linkage specify the potential genetic draw, there is a small chance that a type 0 will mutate to a type 1 or vice-versa. In humans, the mutation rate is one to two

(Strickberger 1985) for a genome of 30,000 genes. We calibrate this rate to our smaller genome and apply it to each gene independently as the final genetic operator.<sup>15</sup>

The single gene for beauty is used because beauty does not affect human capital directly, but does so only indirectly via marriage matching. For this reason, we telescope the many factors that produce physical characteristics into a single index. Because beauty is a scalar, its inheritance dynamics are simpler than that for cognitive characteristics. In particular, a child receives the average of his or her parents' beauty, plus or minus a stochastic disturbance. In this way, beauty runs in families, consistent with evidence that a variety of physical characteristics such as height and weight do (Mueller 1976). Further, this construct biases beauty to be mean-reverting absent assortative mating, but permits some agents to be more or less beautiful than their parents. To accomplish the latter, we use a random draw for noise that is uniformly distributed on  $[-.10, .10]$  while maintaining  $0 < Y < 1$ .

We now construct an agent's human capital as an aggregate of genetic factors, familial nurturing, and education and experience. In this model, education,  $e$ , which we define to include experience, is taken to be a unit mean random variable, capturing formal education and learning-by-doing, and is essentially the earnings shock in Becker & Tomes (1976). Then, human capital of agent  $i$  is

$$h^i = \omega \sum_{j=1}^{50} \alpha_j a_j^i - \theta |b^{ip} - 2| + \aleph e^i, \quad (2)$$

where  $a_j$  is the expression of gene  $j$  (i.e. a zero or one) in the genome  $A$  which is weighted by the monotonically declining sequence  $\alpha_1 > \alpha_2 > \dots > \alpha_{50} > 0$ ,  $\theta \in (0,1)$  is the dilution effect of familial nurturing from having either a single child or more than two children in a family,  $b^{ip}$  is the total number of children agent  $i$ 's parents have, and  $\aleph \in (0,1)$  is the impact of education on human capital. Equation (2) is designed so that genetic factors and education are positively weighted, with  $\sum_{j=1}^{50} \alpha_j + \aleph = 1$ , while parental dilution of nurturing is either zero or negative. The declining series of weights in  $\sum_{j=1}^{50} \alpha_j$  corresponds to the ordering of genes by their importance in the generation of human capital. Traits that are 'off', i.e. are 0, receive no weight in producing one's innate ability. As a result, education does not produce much human capital absent innate ability, consistent with the empirical analysis of education in Hendricks (2000). The linear form for the production of human capital in (2) follows Lucas (1988), and is relatively standard (e.g. Bala & Sorger 1998) since the way biological and environmental components interact is an open issue (Mulligan 1997).

The final parameter in (2),  $\omega \geq 1$ , captures the 'Flynn effect' after Flynn (1987) in which IQ in developing countries has been shown to increase between ten and twenty-five percent in two generations. Wills (1998) argues that the evolution of intelligence is accelerating because of rapid cultural changes, including the ubiquity of visual media, and improvements in child health due to better nutrition and vaccines. The parameter  $\omega$  is included to capture the genetics-environment feedback in a non-Lamarckian manner.<sup>16</sup>



### 2.3. The full model

We now formalize the marriage matching and reproduction aspects described above, as well as specify agents' consumption/savings decisions. All the variables and parameters used are summarized in Table A1 in the Appendix. As is standard, economic variables are written relative to an agent's human capital so that human capital enters the model tractably. This model has a single good that can be used for consumption or investment, with the mathematical structure being quite similar to a standard overlapping generations model (Zak 2000). During childhood one's consumption is chosen and funded by one's parents. For this reason, children do not derive utility during childhood, though their parents receive utility  $\gamma \ln(b)$  from the total number of births,  $b$ , in their family for  $\gamma > 0$ . The cost of raising a child is  $db$ , where  $d$  is the per-child cost (parameterized below as foregone labor income). Agent  $i$  receives utility from consuming  $c_1^i$  as a young adult, and  $c_2^i$  during old-age when he or she is retired. Young adults work, earning labor income  $wh^i$  which is the economy-wide average wage  $w$  times agent  $i$ 's human capital  $h^i$ .

Each agent, whether single or married, makes choices for himself or herself, though married agents' choice sets and constraints differ from that of singles. Success or a lack of it in the marriage market determines which group an agent ends up in since every agent searches for a spouse as a young adult. If agent  $i$  marries agent  $j$  who has pizzazz  $p^j$ , then  $i$  receives the joy of marriage utility  $\pi p^j$ , for  $\pi > 0$  as in Becker (1973, 1974). After marriage,  $i$  and  $j$  are able to reproduce. Couples choose family size by comparing each parent's share of household labor income  $w(h^i + h^j)/2$  with the per parent opportunity cost of children,  $d^{ij}b^{ij}/2$  as shown below. Note that by equally sharing income and expenses, there is no disagreement within a couple over how many children to have, in contrast to Galor & Weil (1996).

When agents' preferences over goods are logarithmic, an agent of type  $i$  born at time  $t - 1$  and potentially married to a spouse  $j$  solves

$$\text{Max}_{c_1^i, c_2^i, \zeta b^{ij}} (1 - \beta) \ln(c_{1,t}^i) + \beta \ln(c_{2,t+1}^i) + \zeta \gamma \ln(b_t^{ij}) + \zeta \pi p^j \quad (3)$$

s.t.

$$c_{1,t}^i = \frac{w_t(h_t^i + \zeta h_t^j)}{1 + 1\zeta} - \zeta \frac{d_t^{ij} b_t^{ij}}{2} - a_{t+1}^i \quad (4)$$

$$c_{2,t+1}^i = R_{t+1} a_{t+1}^i \quad (5)$$

$$b_t^{ij} \geq 2. \quad (6)$$

The budget constraint for agent  $i$  when he or she is a young adult, (4), who is married ( $\zeta = 1$ ) to an agent with human capital  $h^j$  equally shares household income and expenses, consumes  $c_1^i$ , and saves assets  $a^i$  for old-age consumption. The parameter  $\beta \in (0,1)$  specifies the weight placed on old-age vs. young consumption, i.e.  $\beta$  measures patience. If  $i$  is single ( $\zeta = 0$ ), the consumption/savings decision is based on his or her own labor income, absent child-rearing costs. Consumption when  $i$  is old, (5), comes

from the principal and interest on savings as a young adult, with  $R$  being one plus the interest rate. The last constraint (6) limits the number of children that married couples have to be two or greater in order to match U.S. data showing that the average number of children produced by married couples is two (U.S. Census Bureau 1998, Table B).

Because the primary cost of children is the time required to raise them (Birdsall 1988), the cost relation  $d^{ij}$  is parameterized as a function of labor income,

$$d_t^{ij} = \begin{cases} D \left( \frac{w(h_t^i + h_t^j)}{2} \right)^2 & \text{for } \frac{w(h_t^i + h_t^j)}{2} < k \\ D_1 \frac{w(h_t^i + h_t^j)}{2} & \text{for } \frac{w(h_t^i + h_t^j)}{2} \geq k \end{cases} \quad (7)$$

for the constants  $0 < D < \frac{1}{w(h_t^i + h_t^j)/2} \forall i, t$ , and  $D_1 = \frac{\gamma}{2(1+\gamma)}$ , where  $\kappa \equiv \frac{\gamma}{D(1+\gamma)}$ .

This cost function is used rather than modeling parents' time allocation decisions for nurturing children to reduce the number of optimality conditions in the model following Zak et al. (2002) as the resulting effect is the same—as income rises, the desired number of children falls. The cost function is bifurcated because of the lower bound on the number of children, with the change occurring at  $b^{ij} = 2$ . The function  $d^{ij}$  is designed so that agents' economic choices (consumption and savings) do not vary with the number of children in a family, i.e. are identical whether  $b^{ij} > 2$  or  $b^{ij} = 2$  (e.g., see optimality condition (8) below). The bifurcated parameterization of  $d^{ij}$  has no substantive effect on the model's dynamics.<sup>17</sup>

It is convenient to present the solution to the agent's lifetime utility maximization problem in the reverse order in which it is executed. To wit, the optimal solution to (3)–(6) for the amount to save from period  $t$  to  $t + 1$  when agent  $i$  is married to agent  $j$  ( $\zeta = 1$ ) or unmarried ( $\zeta = 0$ ), is

$$a_{t+1}^{i*} = \left[ \frac{\beta}{1 + \zeta\gamma} \right] \frac{w_t(h_t^i + \zeta h_t^j)}{1 + 1\zeta}. \quad (8)$$

Relation (8) shows that savings is proportional to  $i$ 's (share of) household income, rises as patience  $\beta$  rises, and falls as the value placed on children  $\gamma$  increases (since children have a cost). Optimal consumption during young adulthood and old age are found by substituting optimal savings (8) into the budget constraint for each period (4) and (5); let us call these consumption optima  $c_{1,t}^{i*}$  and  $c_{2,t+1}^{i*}$ .

If agent  $i$  is married to  $j$ , the household must also decide how many children to have. The solution for the desired number of children is

$$b_t^{ij*} = \text{Max} \left\{ \frac{\gamma}{D(1+\gamma) \frac{w_t(h_t^i + h_t^j)}{2}}, 2 \right\}. \quad (9)$$

The desired number of children is strictly decreasing in  $i$ 's share of household income due to the opportunity cost of child-rearing, and increases as the preference for children increases. It is straight-forward to show that the desired number of children is (left) continuous at its minimum, two. The decrease in the desired number of children as income rises is consistent with the data (Feng et al. 2000).

Before agents execute their consumption/savings decision, and if married, family size decision, they search a marriage partner. Recall that there are three benefits that accrue to agent  $i$  if she marries agent  $j$ : 1) savings and consumption increase if  $h^j > h^i$  by (8), otherwise, consumption falls; 2)  $i$  receives the utility from children  $\gamma \ln(b^j)$  by (9); and 3)  $i$  receives the joy of marriage utility flow proportional to  $j$ 's pizzazz,  $\pi p^j$ . Note that agent  $j$  receives symmetric benefits if he marries  $i$ . The costs of marriage from  $i$ 's point of view include a potential reduction in consumption (if  $h^j < h^i$ ), bearing half the cost of raising children  $d^j b^j/2$ , and, if  $i$  and  $j$  decide to marry before the final marriage matching round, the inability to meet and marry a different person. Thus, marriage is a relatively standard two-sided matching problem.

Upon meeting, agents simultaneously decide whether or not to marry by comparing indirect utility when married vs. single, taking into account the lost opportunity to marry another agent if the matching market is not in the final round. This choice problem can be clearly seen by examining the final matching round. In the last matching period, agent  $i$  is indifferent between marriage to agent  $j$  and staying single when

$$\begin{aligned} (1 - \beta) \ln(c_i^* |_{\zeta=1}) + \beta \ln(c_{i+1}^* |_{\zeta=1}) + \gamma \ln(b_i^{j*}) + \pi p^j \\ = (1 - \beta) \ln(c_i^* |_{\zeta=0}) + \beta \ln(c_{i+1}^* |_{\zeta=0}). \end{aligned} \quad (10)$$

The left-hand side of equation (10) is the lifetime utility of  $i$  when married ( $\zeta = 1$ ), while the right-hand side is the utility if  $i$  remains single ( $\zeta = 0$ ), where both are evaluated using optimality condition (8) to generate optimal consumption levels, and (9) for the number of children  $i$  and  $j$  would choose to have. Equation (10) indicates that agent  $i$  who meets agent  $j$  in her last round of the marriage market will choose to marry if the right-hand side exceeds the left-hand side (at equality we will assume agents marry).

Before the marriage market opens, that is, when the distribution of types is known but before agent  $i$  has actually encountered a potential mate, equation (10) evaluated at its expected value can be used to find the minimum pizzazz  $i$ 's mate must have to induce her to marry. Let us denote the minimum pizzazz that  $i$ 's spouse must have as  $\bar{p}^j$ . Note that this minimum is agent-specific since it depends on  $i$ 's pizzazz, and is also sex-dependent since males and females differentially value the components of pizzazz (human capital and beauty). Further, a mate's minimum pizzazz also depends on the expectation of meeting a member of the opposite sex—that is, on the sex ratio. For example, if there is a shortage of women relative to men, than a male agent is less likely to meet a woman during any matching round (all the women may be 'taken'). This will cause men to optimally be less 'picky' when determining a mate's minimum required pizzazz. Thus, as the data show, when there is a shortage of women in the marriage

market, women will be more choosy about a mate's attributes and typically marry later in life (Becker 1973, Buss 1994, Seitz 2000). The symmetric result obtains when there is a relative surplus of women.<sup>18</sup>

The analysis above determines a mate's minimum pizzazz in the final round of matching. For the penultimate matching round, taking into account the opportunity cost of meeting a different spouse during the additional matching period, a mate's minimum required pizzazz is higher than the lifetime minimum. Repeating this logic, an agent's minimum pizzazz for a mate is higher than the lifetime minimum for each earlier matching round. In order to reduce the computations in an already computationally heavy model, we use an extrapolation from the lifetime minimum required spouse's pizzazz to determine each agent's minimum spouse's pizzazz in each round of the marriage market.<sup>19</sup> Agents marry if both the man and woman are above the other's minimum pizzazz for the round they are in; otherwise they remain single for that round. Specifically, agent  $i$  who meets agent  $j$  in round  $r$  of the matching game desires to marry  $j$  if

$$p^j \geq \bar{p}^j \exp\left(\frac{\rho - r}{\rho}\right), \quad (11)$$

where  $\rho$  is the number of matching rounds. The marriage occurs if  $j$ 's analog of (11) is also satisfied for  $i$ . Once the marriage market closes, unmatched young agents remain single for the remainder of their lives.

#### 2.4 Production and prices

To close the model, we specify how prices are determined and output is produced. Output  $Y$  is produced with physical capital,  $K$ , and aggregate human capital  $H_t \equiv \int_0^\infty h_t^i d\mu_t$ , where  $\mu$  is an appropriately defined measure over young adults,  $\int_0^\infty d\mu_t = N_t$ , who constitute the labor force. To keep the model's focus on marriage and genetics, we consider this economy to be part of a global system where goods and physical capital flow freely, while human capital (that is, humans) remain in their country of origin.<sup>20</sup>

By assumption, the country under analysis is a sufficiently small part of the global economy that the return on savings,  $R$ , and the economy-wide wage  $\omega$  are set in international markets and are constant over time. Put differently, physical capital that flows in to or out of the country under analysis equalizes factor prices internationally, maintaining a constant ratio of human to physical capital each period. Let the production function be Cobb-Douglas,  $Y_t = K_t^{1-\alpha} H_t^\alpha$ . Then, the ratio of physical to aggregate human capital,  $K_t/H_t$ , is constant at each time period  $t$  due to international flows of physical capital. As a result, output is linear in aggregate human capital,<sup>21</sup>

$$Y_t = AH_t, \quad (12)$$

and output per worker is  $y_t \equiv Y_t/N_t = Ah_t$ , where  $h_t \equiv H_t/N_t$  is average human capital.

From the individual's point of view, he or she is able to transfer resources over time to smooth consumption via the global market for physical capital. Knowing one's human capital and international prices  $w$  and  $R$  is sufficient to solve the consumption-savings-family size decision problem (3)–(6) as well as choose a marriage partner via (10)–(11) taking the expectation over all possible values of a partner's pizzazz  $p^j$ .

### 3. Base model calibration and robustness

Because of the high degree of heterogeneity in the model, we construct the sequence of equilibria numerically using equations (8), (9), and (11), along with the law of motion for human capital (2) and the definition of pizzazz (1). In equilibrium, all agents maximize and prices equate supply and demand in the labor, and capital (savings) markets. Other than the stochastic nature of inheritance and marriage matching, the optimization takes place over a 'smooth' numerical landscape and an economic equilibrium obtains at each point in time. Note that because of the limited number of marriage matching rounds as well as minimum thresholds for a spouse's pizzazz, the marriage market does not clear in each generation (i.e. (11) is not satisfied for all agents), leaving some agents single and unable to reproduce. This is the sexual selection aspect of the model. Further, this means that the 'fertility' market is also not in equilibrium. Put differently, because the model is evolutionary, economic markets are in equilibrium at each point in time but there is not a bioeconomic equilibrium—some agents who wish to marry and have children are unable to do so.<sup>22</sup>

The model is calibrated to replicate U.S. demographic data. This is done not because we seek to replicate U.S. economic data with the model; rather, it is because U.S. demographic data are high quality, available, and reasonably representative of developed-country numbers. The calibration procedure begins by first setting parameter values which are well-estimated in the literature. The remaining parameters are chosen so that the model replicates moments in the data.

We first set the marriage and genetics parameters. Buss (1989) reports results from surveys of individuals in the U.S. on mate preference which permits a determination of the relative weights men and women put on human capital versus beauty when choosing a mate,  $\eta_m$  and  $\eta_f$ , in the pizzazz equation (1). Isolating the effects on matching of earning ability and attractiveness, the following values arise:  $\eta_m = .34$ , and  $\eta_f = .54$ . Thus, when evaluating a prospective marriage partner, men value beauty almost twice as much as human capital (66% vs. 34%), while women value human capital and beauty nearly equally (54% to 46%). This is consistent with the discussion above of the biologically-driven differences in parental investment in offspring. The number of marriage matching rounds is set to twelve.

Next, we draw on the behavioral genetics literature to identify the parameters in the human capital production function (2). The weighting parameters  $\alpha_j$  for

$j = 1, 2, \dots, 50$  for the genetic constituents of human capital are chosen as a declining geometric sequence satisfying  $\sum_{j=1}^{50} \alpha_j + \aleph = 1$ . Plomin (1994) estimates the weight  $\aleph$  on education to be .25. The education variable is specified so that  $e \sim N(1, .25^2)$ , indicating that the sequence  $\{\alpha_j\}$  is chosen with  $\sum_{j=1}^{50} \alpha_j = .75$ . Lastly, the dilution effect on parental and child-to-child nurturing in families that do not have two children,  $\theta = .02$ , according to Behrman et al. (1980, Tables 6.7 and 6.8) who estimate earnings regressions similar to equation (2).

Flynn (1987) shows that IQ scores have increased between 10% to 25% over the last two generations in developed countries. Taking the mean increase to be the average of .10 and .25 and dividing by two to find the increase per generation indicates that gene-culture co-evolution causes average human capital to increase 9% per generation. The parameter  $\omega$  is chosen to match this effect each generation when fertility is at its replacement rate. Thus,  $\omega$  is set so that  $\omega E[\sum_{j=1}^{50} \alpha_j a_j - \theta(3.3 - 2) + \aleph e] = 1.09$  which is the expectation of human capital equation (2) evaluated at population replacement fertility.<sup>23</sup> The resulting value for  $\omega = 2.31$ .<sup>24</sup>

The patience parameter  $\beta$  can be calculated from values used in the real business cycle literature. A standard value for the subjective discount rate is 1% per year (Cooley 1995). Considering a generation (a 'period' in our model) to be twenty years, the equivalent discount factor is  $.99^{20} = .818 = \beta$ . The remaining parameters are either used to calibrate the model or set to innocuous values if there is insufficient data to evaluate them. For the latter reason, we set the cost of children scale factor  $D = .3$ , the production function constant  $A = 1$ , and the joy of marriage parameter,  $\pi = .1$ . Lastly, we choose the parameter for the utility of children,  $\gamma$ , and the constant average wage  $\omega$  so that the model replicates the 60% marriage rate in the data, and produces an endogenous fertility rate that leads to a roughly constant population for twenty generations. We found this combination of  $\gamma$  and  $\omega$  via a grid search that produced the closest match to these two data points. A constant population is important for the base model so that the effect on society of institutional changes that impact marriage and fertility in the experiments that follow can be clearly discerned. The resulting values are  $\gamma = .0125$  and  $\omega = .218$ .

To begin the simulations, we need to generate initial data for the economy. The initial distribution of genetic material  $a_j$  at each location  $j$  is generated via a 50–50 draw for zero or one. The exception to this rule is the linked genes 10 and 11. When 10 is generated, 11 inherits this value. We randomly generate an initial distribution of genetic material in this way in the absence of information suggesting a better biological fit. Lastly, the distribution of beauty,  $Y$  is uniform on  $[0,1]$ , producing an initial mean beauty of 0.5.

As discussed in Section 2.2, because of the length of time to solve this model computationally and need for sufficient genetic diversity to produce useful results, the initial population size is set to 300 agents. Increasing the number of agents above this substantially slows processing time without altering the results. For each institutional change reported below, we generate the identical set of random variables so that, though the environment in which agents make decisions is stochastic, different realizations of stochastic variables do not drive the results.

### 3.1. Base model results and sensitivity analyses

Running the base model for 40 generations, we find output grows over time as aggregate human capital accumulates, with a geometric output growth rate of 1.6% per generation. Figure 1 shows that output growth is not monotone. The dips in output shown in the figure are caused by variations in the marriage matching rate which follow from two sources: the stochastic nature of inheritance which affects the distribution of human capital, and the random nature of marriage matching which causes variations in population size across generations. When marriage matching falls, aggregate fertility declines, reducing the size of the labor force in the following generation and, for a given level of aggregate human capital, reducing output. For example, in generation 17 the marriage rate falls to 62% from 71% in generation 16. As a result, aggregate births fall 10% and aggregate output declines by 5%.

This simulation exhibits positive assortative mating as the standard deviation of human capital falls by 27% during the forty generations, and average beauty rises by one-third. As a result, average pizzazz increases 45%, primarily driven by the growth in human capital. Mean human capital, which is per worker output, strictly increases throughout this simulation, growing steadily at 1% per generation. Indeed, because human capital is unbounded while beauty is bounded above by unity, as living

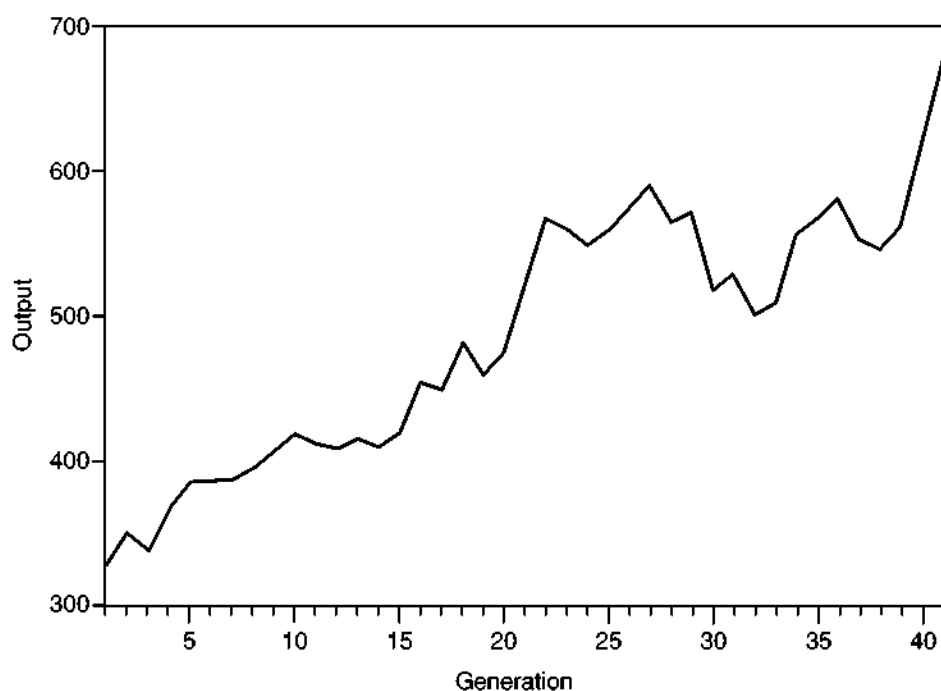


Figure 1. Aggregate output of base model.

standards increase, human capital causes pizzazz to grow, while beauty is bounded from above. Agents still desire beautiful spouses, but a growing economy is the result of the growth of ‘brains’ not beauty, and this is reflected in mating behavior.

The baseline model appears to be a reasonable representation of societal and economic growth over the past 800 years (40 generations times 20 years per generation). Next we undertake a sensitivity analysis to determine the model’s robustness. To do this, we increase and decrease each parameter in the model by 10% with the identical set of stochastic shocks and calculated the  $R^2$  for OLS regressions of output between the base and perturbed models over 20 generations.  $R^2$ s for most of the runs exceed .75. The model is most sensitive to the joy of marriage parameter  $\pi$  ( $R^2 = .50$ ) and the utility of children parameter  $\gamma$  ( $R^2 = .60$ ), both of which we have a paucity of data to use in determining their values.<sup>25</sup>

As an additional sensitivity check, we ran the model 100 times using the base model parameters and 100 different random sequences of stochastic shocks. The  $R^2$  between the base model and the average time series from these 100 runs is .85. These sensitivity analyses indicate that the model is fairly robust to small perturbations. None of the various scenarios that we examine in Section 4 involve changes in any of the parameters to which the model is sensitive.

#### 4. Responses to institutional and environmental changes

In the following subsections, we examine a variety of environmental and institutional changes that impact marriage and fertility, and subsequently societal performance over time. To reiterate: the impact on societal performance occurs as institutional factors affect the rate and types of marriages that are formed and therefore the production of humans and of human capital, with these effects cumulating over generations.

##### 4.1. Inequality

The first policy experiment we undertake is to vary the initial distribution of human capital so that income inequality increases. The relationship between inequality and economic performance is a current area of controversy with rising inequality generally reducing growth (Forbes 2000, Perotti 1996), and it is therefore worth examining. We perform this exercise by changing the initial distribution of genetic material. Rather than generate agents’ genomes in the first generation by a 50–50 draw, we split the sample so that half the agents have a 60–40 draw for a 1 at any particular location, and the other half have a 40–60 draw for a 1. This changes the initial distribution of human capital relative to the base model; though the means are the same, the variance of initial human capital for this experiment is 65% higher. All other aspects of the economy are unchanged.

Following this economy for 70 generations, aggregate output exceeds the base model until generation 8 as shown in Figure 2. At this point, the downward pressure on fertility from rising incomes is not matched by an increasing marriage rate as in the



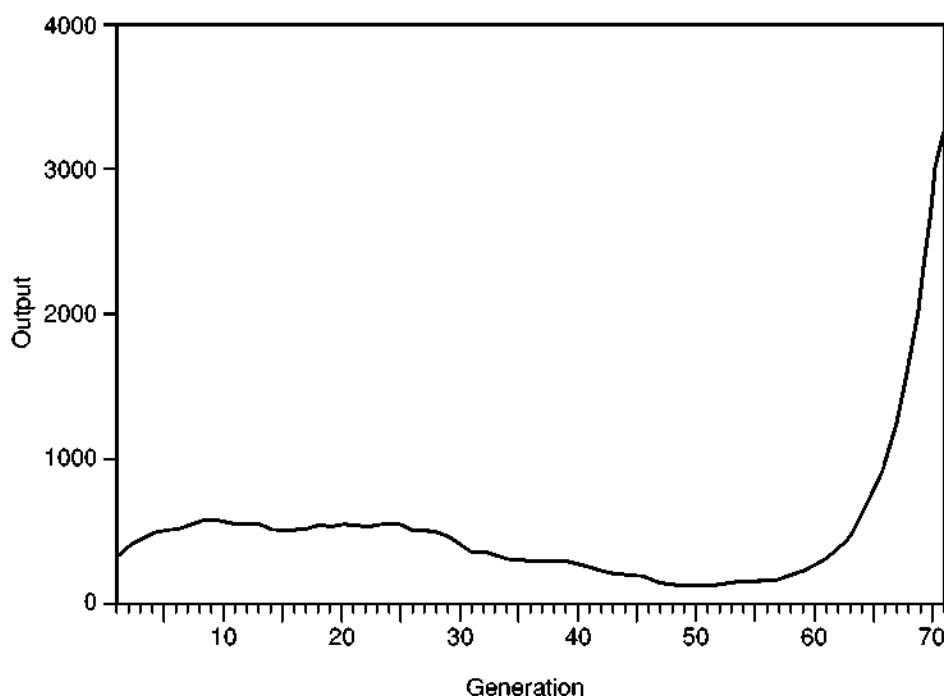


Figure 2. Aggregate output with increased inequality.

base model, causing population and aggregate output to fall. Income per capita continues to rise, even as aggregate output falls, further decreasing the fertility rate and leading aggregate income to be 63% lower than the base model by generation 49. The decline in output is driven by a shrinking workforce; between generation 1 and generation 49, the number of young adults falls 80%. In this simulation, the increased heterogeneity in human capital results in a lower marriage rate, leading to an epoch of contraction. Nevertheless, by generation 61, output recovers its initial level as the marriage rate rises rapidly beginning in generation 50, and with it aggregate fertility and the size of the labor force.

The growth slowdown occurs because of a decrease in marriage rates and reproduction due to inequality—there are simply fewer agents who meet others' marriage criteria. This changes when the number of agents shrinks sufficiently; agents optimally become less picky when the population is small. For example, after the population bottoms-out in generation 49, the marriage rate for the remaining generations is very high, ranging between 80–91%. Concomitantly, the average difference between spouses' human capital rises revealing looser marriageability standards. Interestingly, the variance of the distribution of human capital at generation 40 is identical to the variance for this generation in the base model. Nevertheless, the long period of economic decline is the result of the cumulative impact of low marriage rates.

A second experiment uses the male-female asymmetry in the evaluation of pizzazz to examine the effects of inequality in beauty. In this experiment, we vary the initial distribution of beauty to produce a society with a proportionally larger number of very beautiful and very plain agents of both sexes. To do this, we change the initial distribution that generates beauty from uniform to bimodal. A simple way to generate a bimodal distribution is by taking a uniform distribution and applying a mean-preserving spread. We generate an agent's beauty in this experiment as  $.5 + .05 \times \Delta$ , where  $\Delta$  is a random variable that takes values  $-1$  or  $1$  with a 50% probability. The initial distribution of human capital for this simulation matches that in the base model, so that the only difference in this economy is the initial distribution of beauty.

Running this economy for 70 generations we find that aggregate output initially exceeds the base model, but begins to fall in generation 5 as a lower marriage rate coupled with the negative impact on fertility of income growth for young adults causes the population to shrink. Indeed, after 37 generations the labor force falls 92% and aggregate output is 86% below its initial value. By generation 40, the population of young adults is so small that agents optimally widen their criteria for an acceptable spouse. This causes the marriage rate to increase, raising aggregate fertility as in the previous case. By generation 50, the trend is strongly upward, and aggregate output and population grow apace. By generation 64, the economy has recovered the initial level of output. The plot of aggregate output for this experiment qualitatively matches the graph in Figure 2, though output is less than in the previous case throughout this simulation showing the powerful effect that beauty has on sexual selection, fertility, and output.

Because of the importance of genetic diversity in biology and income inequality in economics, we undertake a further set of studies of the relationship between inequality and economic output using two different approaches. The first method changes the probability of getting a 1 rather than a 0 at each location in initial agents' genomes stepwise away from .50. This produces an increase in the variance of human capital (i.e. greater genetic diversity) in the initial generation of agents while keeping the mean roughly constant and the distribution unimodal. The second approach splits the sample so that one-half of the agents have a probability  $p_1$  of having a 1 in each location in their genomes, while the other half of the population have probability  $1 - p_1$  of a 1 at each position. This approach also increases the variance of the initial human capital, but does so by producing a bimodal distribution.

Figures 3a and 3b show the relationship between genetic diversity and economic performance. As the variance of the unimodal distribution rises (Figure 3a), average output growth over 20 generations falls monotonically. When a society's size and productivity depend on sexual selection as in this model, greater genetic diversity reduces the marriage rate monotonically, and population size and output therefore fall. Note that average output growth per generation is negative over each 20 generation run when the standard deviation of initial human capital exceeds .12.

Intriguingly, the same result does not obtain when genetic diversity increases bimodally (Figure 3b). In this case, as aggregate diversity rises, the marriage rate, population

size, and output growth all initially fall over 20 generations, but then when the standard deviation of initial human capital exceeds .33, marriage, population size and output growth all rise with further diversity. This produces a U-shaped relation between genetic diversity and output growth. This surprising result is driven by the decreasing diversity within a mode (or niche) as the variance rises which enhances the ability to find a suitable mate within that niche. Further, output growth over 20 generations is positive for most variance levels, except for those near the minimum of the U-shaped curve, unlike the previous case with a unimodal distribution in which increasing genetic diversity most often led to a contraction in population and production. Figures 3a and 3b demonstrate the complicated relationship between genetic diversity and a species' ability to flourish.

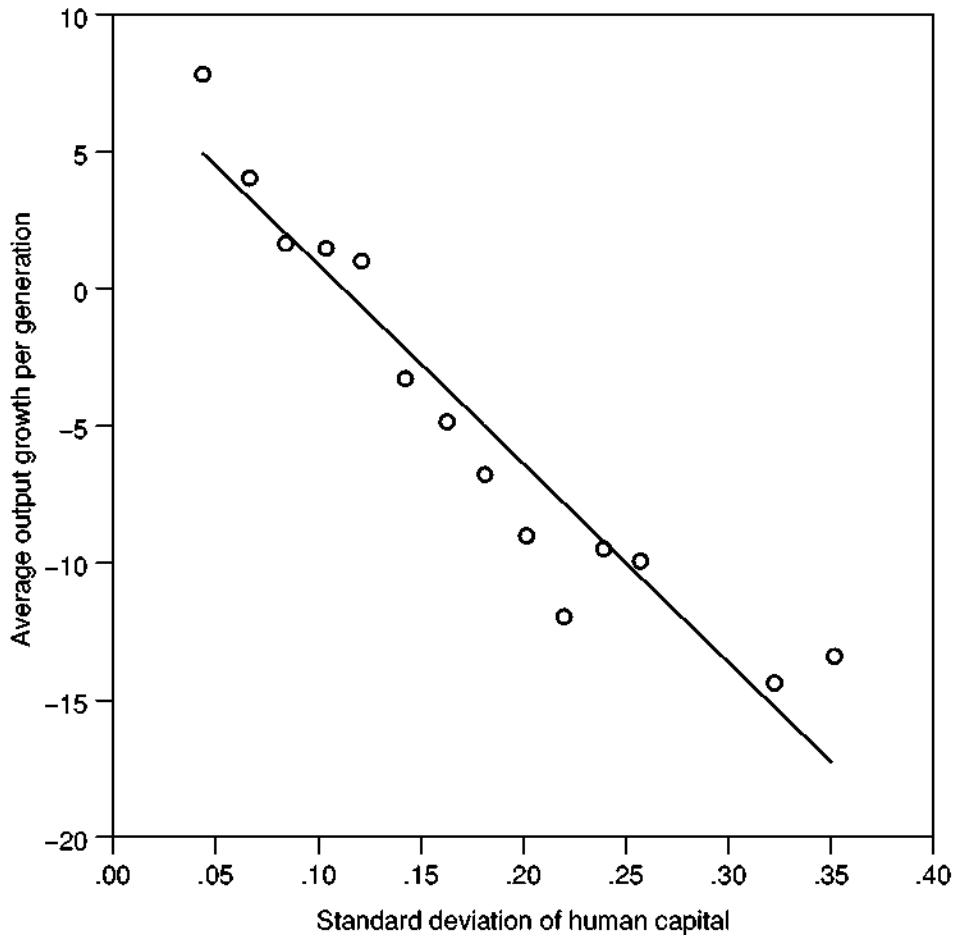


Figure 3a. Unimodal genetic diversity and economic performance.

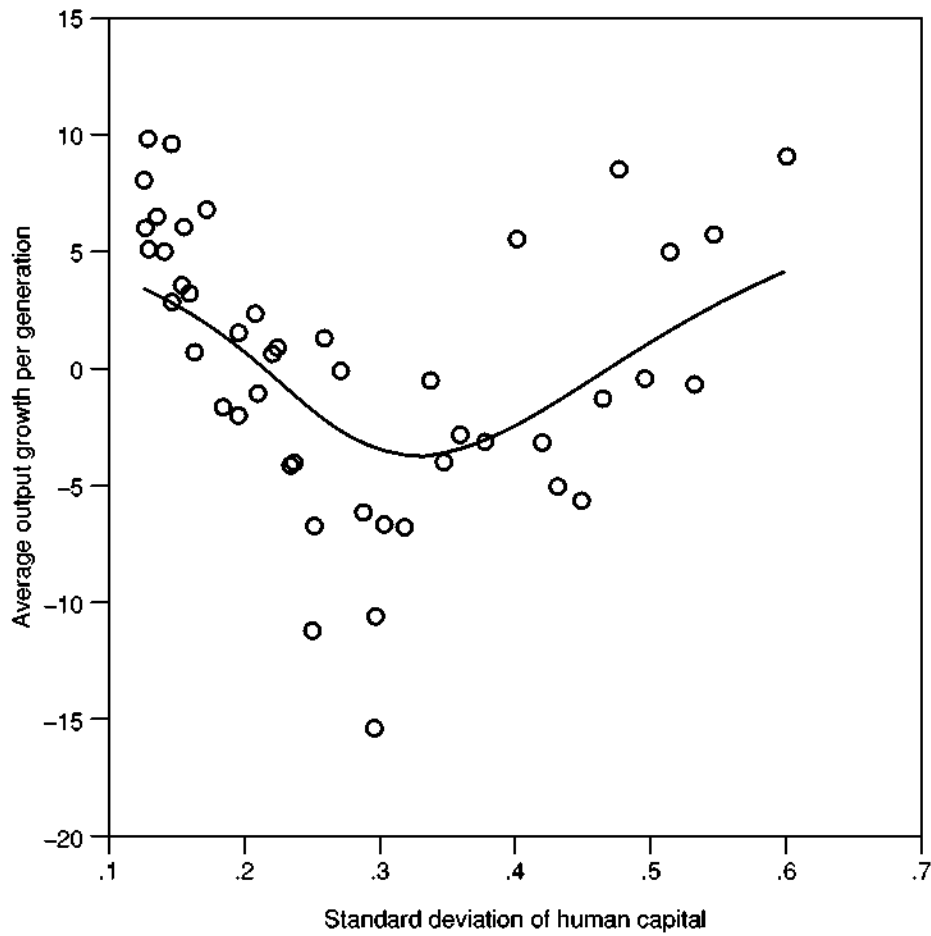


Figure 3b. Bimodal genetic diversity and economic performance.

In these experiments we find that in aggregate, increased inequality may or may not adversely affect society. More generally, we find that increasing kurtosis in the initial genetic distribution enhances population and production, whether the distribution is unimodal or bimodal as greater kurtosis raises the marriage matching rate. The emergent property of a nearly 100% marriage rate when the population is on the verge of extinction that appears in the scenarios in this section recurs in the simulations we run subsequently and is a consistent part of the complex dynamics of this model. This endogenous threshold is a critical stabilizing factor for societies, and derives from sexual selection optimized to environmental conditions.

#### 4.2. *The change from an industrial to an information economy*

This simulation examines the effect on population and economic performance when the labor market changes its valuation of the components that produce human capital  $h^i$ . Consider a society that has run for 20 generations as an industrial power where a certain type of worker (e.g. manufacturing) is highly valued. (We run the economy for 20 generations before making a change so that initial conditions do not affect the results.) Then, an information revolution occurs so that ‘nerds’ rather than manufacturing workers are highly valued in the labor market. This corresponds to a change in the weights placed on the genetic constituents of human capital,  $\alpha_j$ . That is, this is not a genetic change, but a change in the market valuation of various genetic factors that produce human capital (‘brains vs. brawn’).

In this simulation, the weighting in the production of human capital for children in generation 21 changes from  $\alpha_1 > \alpha_2 > \dots \alpha_{50}$  to  $\alpha_{50} > \alpha_{49} > \dots \alpha_1$ . That is, society’s valuation of innate attributes reverses in period 21. Presumably, the change in values for various attributes during the information revolution in the twentieth century occurred slowly, but we undertake this radical experiment to generate stark results. Intuitively, this change fundamentally affects marriage and fertility decisions—now ‘nerds’ rather than craftsmen are the hot properties on the marriage market, inverting the previous pattern of assortative mating. In every other way, this economy is unchanged from the base model.<sup>26</sup>

Figure 4 plots aggregate output for 70 generations for this society. It shows that there is an extended decrease in aggregate output beginning in generation 21, and continuing until generation 40, while per capita income drops but quickly recovers. In generation 21, the variance of human capital in the information economy is 350% higher than in generation 21 of the base model. Though ‘nerds’ who suddenly have high incomes are prized on the marriage market, finding a suitable marriage partner is now more difficult. After the information revolution, the average difference between spouses’ human capital rises, evidence of matching difficulties, and the marriage rate falls for 20 generations. Population and output decline until a sufficiently small population results in an endogenous, through sluggish, renewal of population and output. Output does not recover its prerevolution (generation 20) level until generation 64.

This result is sensitive to the weights placed on the genetic components of the new high human capital agents. In the experiment discussed above, weights were inverted, but unchanged in their sequence of values. If, on the other hand, the weights on the previous low values are raised after the inversion (i.e. ‘nerds’ are more highly valued than were industrial workers, with the weights continuing to sum to 0.75), after an initial growth spurt following generation 20, inequality rises which reduces the marriage rate, causing output to more sharply decline than in the previous case. As before, increased diversity in human capital triggers declines in marriage and reproduction, with aggregate output following this downward path. For a 15% increase in the weights on the first 10 genetic factors, aggregate output declines more sharply than in the previous case, and does not recover its generation 20 level until generation 69. Thus, the model indicates that productivity gains from the recent information revolution are

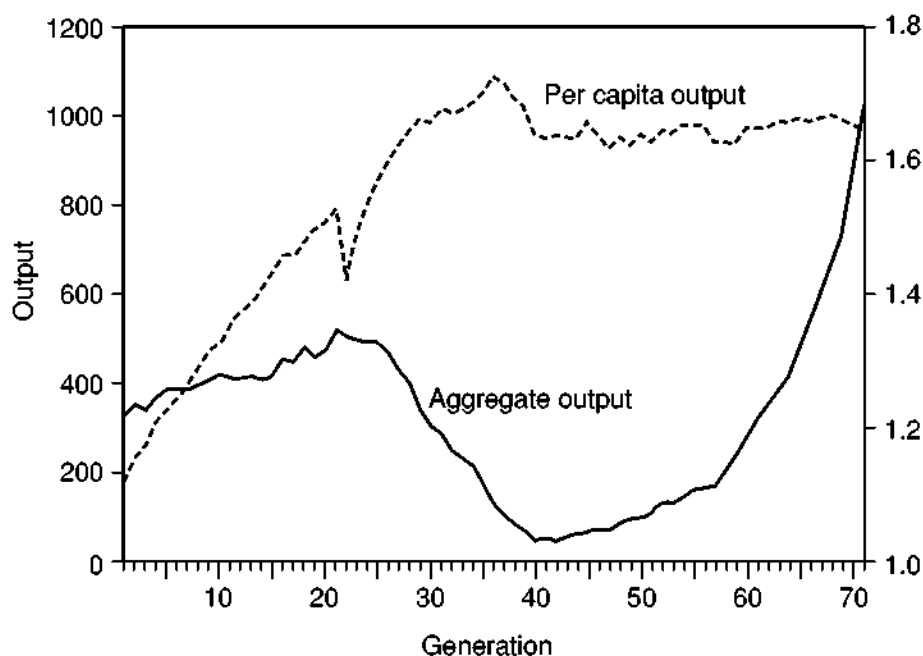


Figure 4. The change to an information economy.

considerable since they have offset what otherwise would have been a substantial economic decline due to sexual selection predicted in this variant of the model.

#### 4.3. Population bottlenecks

When an extreme environmental event, such as a pandemic, kills off a large proportion of a species so that the remaining group inbreeds, genetic adaptations and anomalies cumulate.<sup>27</sup> This type of environmental selection pressure, known as the *founder effect*, causes a twist in this branch of the genetic tree. Examples include Tay-Sachs disease in Ashkenazi Jews, and colorblindness in Pingelap Islanders. We investigate such a twist by considering an environmental change that within a generation kills a large proportion of the population in several particular ways.

These variants of the model examine the effects of events like the Black Plague that killed 25 million in fourteenth century Europe, where people ate 'lunch with their friends and dinner with their ancestors in paradise' (Boccaccio 1351). The first scenario we consider is a plague that randomly kills one-half of the young population before they are able to marry and reproduce in the twenty-first generation, after twenty generations of plague-free evolution. In this case, we find that aggregate output falls 23% in generation 21 and continues downward (with slight upticks) until

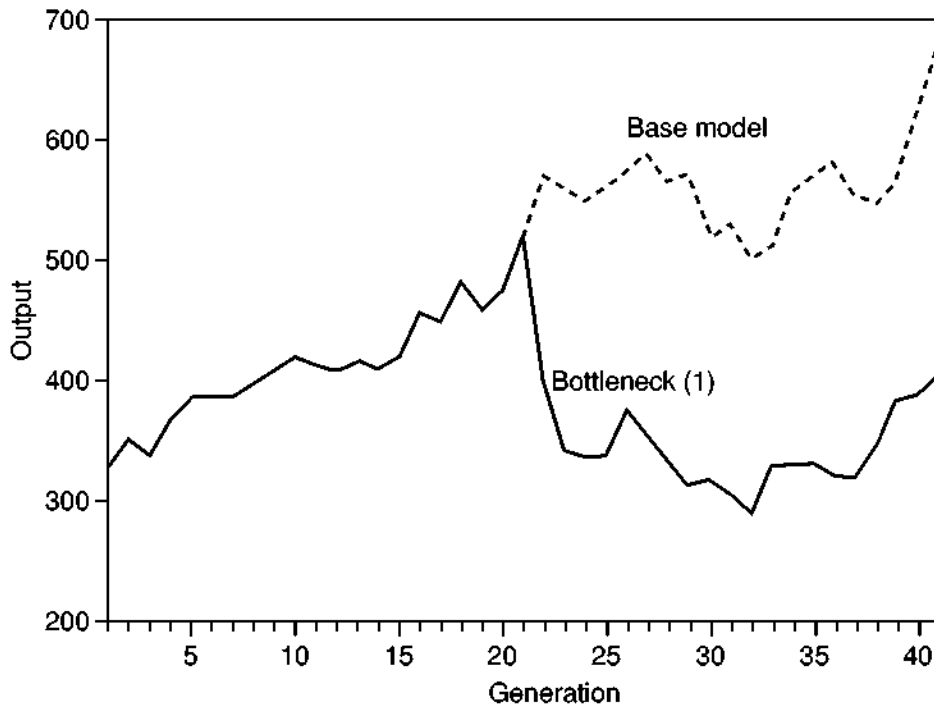


Figure 5. A population bottleneck (Scenario 1).

generation 31 when an upward trend is re-established (Figure 5). By generation 45, output recovers the level it was at in generation 20. The slow recovery of the economy occurs because marriage rates plummet and remain low until after generation 30 while income per capita continues to rise following the plague, with both effects keeping fertility low.

In the second variation, rather than having the plague kill agents randomly, disease kills agents who do not possess a congenital immunity.<sup>28</sup> We model this by positing that agents who have 19 or more 'on' genes in *even locations* on the genome are immune to the pandemic.<sup>29</sup> The value of 19 was chosen so that roughly half the population would be killed in the plague, matching the first population bottleneck. As above, we run the simulation for 20 generations and then let the plague hit young adults before they enter the marriage market. Figure 6 shows that output initially falls 45%, recovers and falls again, beginning an upward trend in generation 30. In generation 43, this society recovers the generation 20 level of aggregate output. Interestingly, in generation 40, the distribution of human capital for the post-plague society has the same mean and variance as the base society in generation 40, though the former is slightly skewed leftward. Thus, the plague has little effect on the composition of human capital, with its primary effect being a reduction in the size of the labor force.

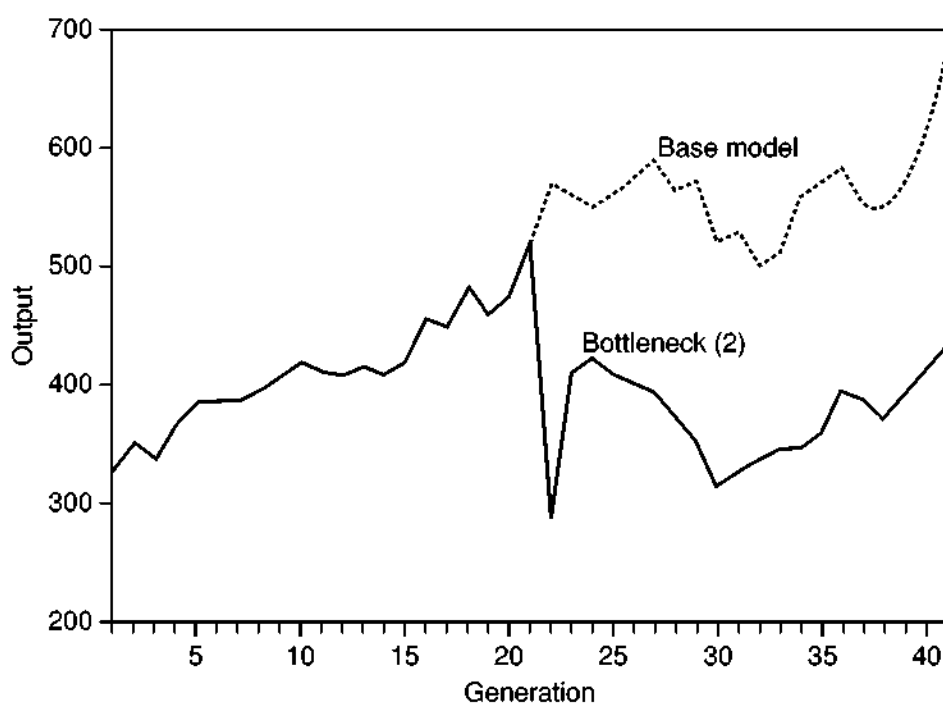


Figure 6. A population bottleneck (Scenario 2).

The final bottleneck we examine is gender specific. In this experiment, the disease only infects men, barring a high degree of immunity. For example, there is evidence that common viruses such as Epstein-Barr (which causes mononucleosis) may be fatal to boys with an X-linked immunodeficiency (Purtilo et al. 1975). In this experiment, only young males who have less than 19 'on' genes in even locations die; females are completely immune. As before, the disease-free economy runs for 20 generations, and the plague hits young males in generation 21 prior to reproduction. Two generations after the plague hits, output falls 33% as Figure 7 depicts, and recovers its pre-plague level by generation 34. Immediately after the plague, an asymmetry appears in marriage matching rates. The 72% marriage rate for males and females in generation 20 changes to a 59% rate for males, and 40% for females. Within two generations, the marriage rate recovers to a symmetric 70% and continues to rise, even as fertility slowly declines as per capita income rises.

In all three population bottlenecks examined, output falls by less than does the population, keeping per capita incomes high, even as nearly half of the population is killed. Although the aggregate effects are substantial, living standards for survivors are relatively unaffected. A society hit by a gender-specific pandemic has the most rapid recovery in population and output as the remaining disease-free individuals are highly



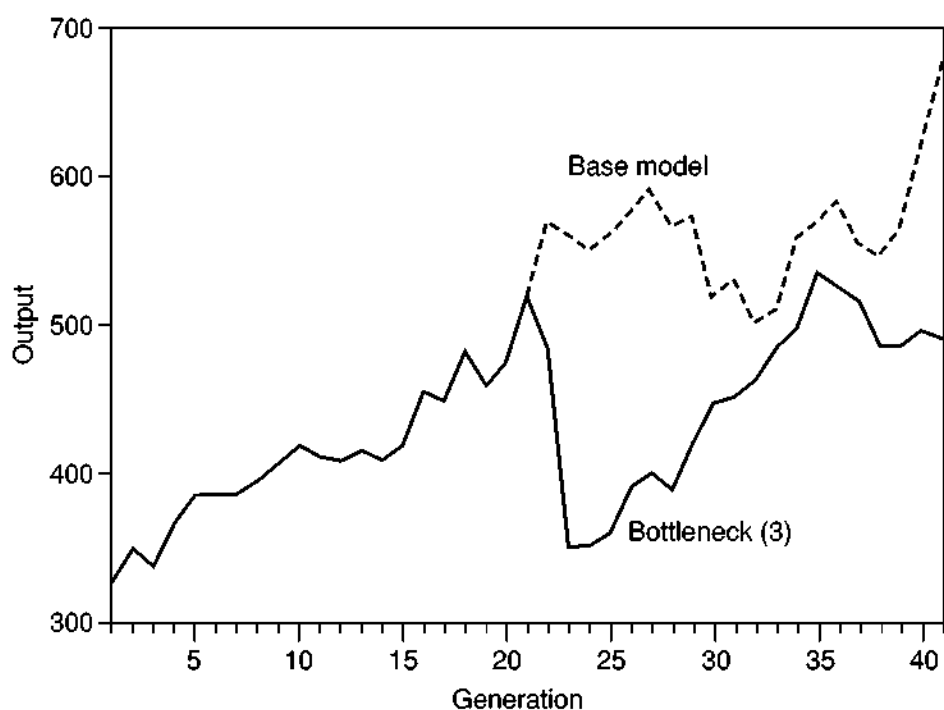


Figure 7. A population bottleneck (Scenario 3).

valued on the marriage market. A society with a genetic immunity to disease is shown to recover more quickly than a population hit by an indiscriminate plague. Overall, pandemics do not appear to have permanent effects vis-à-vis population size, the distributions of human capital and beauty, or output levels.

#### 4.4. Endogamy

In this section we examine the aggregate impact on fertility and output of endogamy (marriage between similar types). Endogamy arises due to geographic segmentation of the population or other barriers that inhibit meeting a broad set of potential spouses. Endogamy can be thought of as a matching technology that changes the matching set from global to one defined only over a certain subset of the population.<sup>30</sup> Technologies that facilitate endogamy include matchmakers and dating services that permit individuals to sort themselves and prospective mates into identified categories. For example, the most popular internet dating site, Match.com, permits individuals to search for potential mates by a variety of characteristics including age, location, education, and a desire for (or not for) children. Match.com enables individuals to anonymously email

each other to determine compatibility, leading in some cases to phone calls and eventually tête-à-tête meetings. In the year 2000, this site had over 925,000 active members and six million visitors. Since its inception in 1995, Match.com has facilitated 160,000 'meaningful relationships' and more than 900 marriages. A similar internet dating site that specializes in matching alumni and faculty from the Ivy League is GoodGenes.com.

The 'sorting' aspect of endogamy is built into the model by limiting the random meeting of agents to only those similar to themselves, where 'similar' is defined by the degree of segmentation of the population as shown below. Once a couple meets, both choose whether to marry using criterion (11); couples are never compelled by outside forces to marry. For simplicity, we ignore any costs associated with meeting potential spouses in an agent's marriageable group.<sup>31</sup>

Figure 8 plots aggregate output when there are three subgroups of agents such that one can only meet a potential marriage partner from the group one is in. The figure shows that output initially peaks in generation 2, then declines steadily as the population falls until generation 34, after which the marriage matching rate rapidly rises, raising aggregate fertility even as fertility per household falls steadily over time. The endogenous recovery of population and output when the agent set is sufficiently small

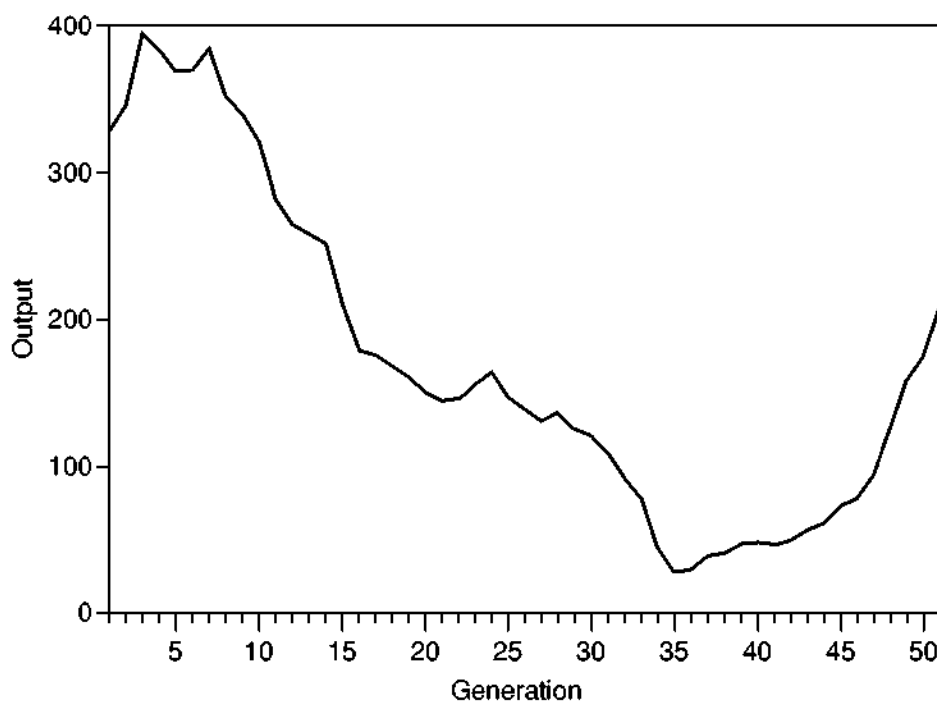


Figure 8. Aggregate output with endogamy.

matches that seen in other simulations. By generation 52, output recovers its initial level and population and output continue to grow. This simulation shows that endogamy increases inequality among individuals (i.e. the variance of human capital rises through the first 30 generations), and reduces the marriage rate over many generations.

The experiments with endogamy, inequality, and population bottlenecks suggest that when population is shrinking, the threshold at which the marriage rate endogenously recovers and population begins to grow is around 40 agents. That is, 40 individuals is the minimum viable population in this model which appears to be a repelling equilibrium. Agents optimally loosen the thresholds for an acceptable marriage partner when prospects are scarce, and for a population near 40 we see that the average difference between spouses' human capital rises rapidly—'opposites' are matching—which keep society from extinction. To investigate this issue further, we reran the endogamy experiment increasing the number of subgroups from which one can meet a mate from three to five. This puts an additional friction on matching opportunities. After 29 generations, this society becomes extinct; there are no marriages and therefore no reproduction. The high degree of endogamy in this case disallows agents in a small society from marrying those who remain, leading to its demise. This demonstrates the value of freedom of choice in mating among a large and genetically heterogeneous population.

#### 4.5. *Love*

In this section we examine the effect of love on marriage in a manner similar to Becker (1974), and characterize its impact on population size and economic performance. Even though the basic model includes both beauty and the joy of marriage, these are not 'love' because they are part of a purely rational decision process. Indeed, pizzazz is an index of *attraction* by the opposite sex to an individual that Darwin (1871/1981) considered distinct from, though related to, the emotion love. The outstanding feature of love is that, though it has many dimensions, one is either in it or not.<sup>32</sup> Love is a 'biological imperative' (Ackerman 1995) because it is the mechanism that guarantees the perpetuation of genes. Buss (1994, p. 42) writes that: "Love is one of the most important cues to commitment", and therefore signals to a potential mate whether one will remain in the relationship—a critical cue when choosing whether to marry and have children.

By including love in the model we seek to take into account the impact of the emotions on mate choice. Following Becker (1974), we expect love to decrease the degree of positive assortative mating. That is, we expect the average difference in human capital between married men and women to be higher with love than without. Thus, this is a model of (partial) exogamy.

We include love in the model, while maintaining some rationality in mating choices, by making two assumptions. First, being in love does not necessarily lead to marriage. That is, one can meet and fall in love with someone, but not find them a compatible long-term mate. The second assumption is the partial converse of the first: No matter

how high a potential mate's pizzazz may be, marriage does not occur unless the man and woman are both in love. We operationalize this approach by having each agent in the model determine the minimum pizzazz a mate must have in the final matching round, as in the base model, but this minimum is not scaled up for earlier rounds of the marriage market. Instead, we introduce a random variable  $\heartsuit^{ij} \in \{0, 1\}$  that indicates whether agent  $i$  is in love with agent  $j$  ( $\heartsuit^{ij} = 1$ ), or is not in love ( $\heartsuit^{ij} = 0$ ).<sup>33</sup> Upon meeting, agents  $i$  and  $j$  marry in any matching round if they are both above the other's final round minimum mate's pizzazz ( $p^{ij} > \bar{p}^{ij}$  and  $p^{ji} > \bar{p}^{ji}$ ), and both agents are in love with each other  $\heartsuit^{ij} = 1 = \heartsuit^{ji}$ . In the absence of a theory of love (rather than attraction, which is pizzazz), the variable  $\heartsuit^{ij}$  is generated for each agent in each matching round with a 40% chance of being a 1. We use a 40% value as we are unable to assign a probability distribution to this variable from a review of the literature. Below we discuss the sensitivity of our results as this probability changes.

Figure 9 plots aggregate output for the model with love. The figure shows that the inclusion of love causes income to grow spectacularly. After 40 generations, this economy more than quadruples in size, with a growth rate of 3.7% per generation (versus 1.6% per generation for the base model). Moreover, the growth rate accelerates to 5.6% during the generations 25–40. This by far exceeds output growth in any other of

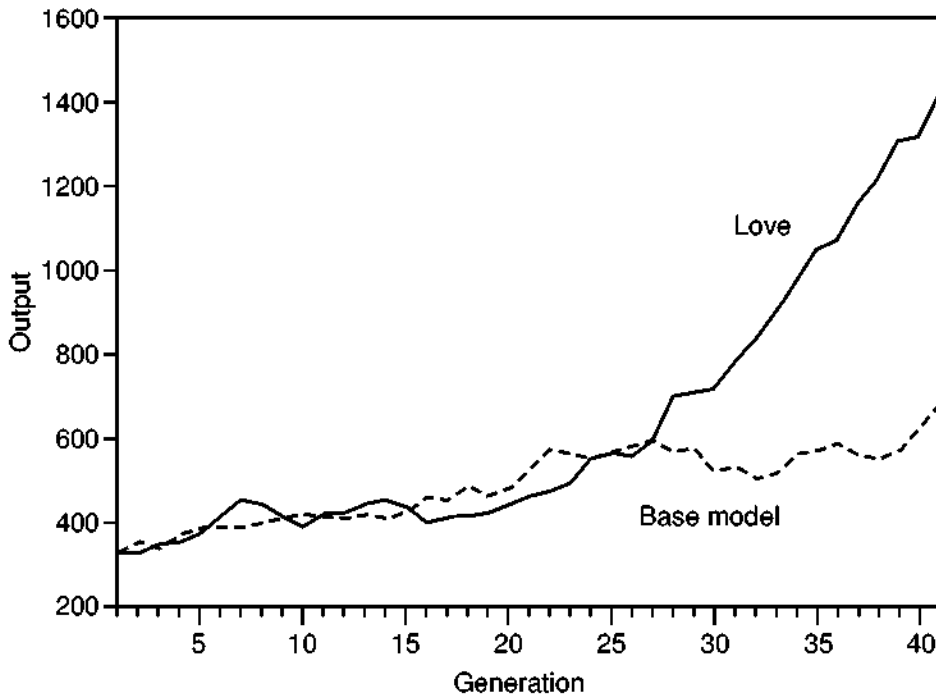


Figure 9 Aggregate output with love.

the experiments we consider. This dramatic result occurs as love generates positive assortative mating while maintaining sufficient genetic diversity among couples (and their children). Measuring household diversity by the average difference between spouses' human capital, household diversity is 25% larger over 40 generations for the model with love relative to the base model.

If the probability of falling in love with a member of the opposite sex rises above 40%, the number of marriages—as well as population and output—increase even more rapidly than in the previous case. As the probability of falling in love falls, the number of marriages, population, and output growth also fall. For example, if the probability that  $\heartsuit^i = 1$  is below 17%, then output falls for nearly 40 generations before slowly recovering. Thus, an economy in which agents are unlikely to fall in love suffers a sustained contraction in output.

Love balances an increase in genetic diversity with a strong desire to mate assortatively. The result of this balance is rapid output and population growth. We call love's balancing of assortative mating and genetic diversity. The Goldilocks Principle as this emotion appears to mix these two opposing effects so the result is 'just right'. This contrasts with a pure decrease in genetic diversity that Section 3 shows typically reduces output growth. Thus, the model suggests that love is important to social and economic performance.

## 5. Conclusion

We have set out a model of population genetics in order to characterize the effects that marriage and reproductive choices have on societies. One of the contributions of this paper is the framework linking genetics, and more generally the bioeconomics of the family, to economic growth. The model shows that in every environment, positive assortative mating obtains to various degrees, but the marriage rate may be so low that population and aggregate output fall for extended periods of time. Inequality, including that induced by endogamy, is shown to induce long periods of economic contraction, as do population bottlenecks. Absent these, marriage and fertility lead to nonmonotone, though generally positive output growth.

The model indicates that there is a balance between increased genetic diversity which often reduces the marriage rate, and the ability to positively assortatively mate which generally increases the marriage rate. Indeed, one of our primary findings is that diversity and population size have a nonmonotone relationship. To wit, population and production grow most rapidly when diversity and positive assortative mating are properly balanced. Including the emotion love in the model appears to do just this in a Goldilocks manner: population and output growth are both very rapid when marriage matching also includes love. We also find that absent a severe matching friction, agents' marriage matching optima keep the population from extinction even after many generations of decline when an endogenous threshold of population size (around 40 individuals) is reached which substantially raises the marriage rate, initiating and sustaining growth in population and production.

The model generates a number of empirical testable hypotheses that have either been found in other research, or deserve further study. These include: Low status men marry at a lower rate than others (Buss 1989); Attractive women marry higher human capital men (Hammermesh & Biddle 1994); Recovery from plagues depends on immunity patterns; Greater variance in human capital reduces marriage rates for unimodal human capital distributions and also reduces economic growth, while the relationship between human capital variance, marriage, and economic growth is nonmonotone for multimodal distributions; The marriage rate spikes upward when societies become sufficiently small; and, Societies that include love in the marriage decision have greater spousal diversity and higher rates of economic growth.

The bioeconomic approach developed here can be extended both in its biological foundations by modeling explicit genes as base pairs (e.g. see Banzhaf & Eeckman 1995), in the environmental factors examined, and in the way agents are identified. This should not affect, though, the primary results of the paper: both excessive inbreeding and excessive diversity reduce the marriage rate and can lead to epochs of decline.<sup>34</sup> More generally, we have shown that the social-economic-institutional environment matters because it affects decisions by the human animal—decisions driven by our evolutionary makeup—leading to a genetics-environment co-evolutionary cycle.

## Appendix

Table A1. Variables and Parameters

VARIABLE	DEFINITION	RANGE
$i$	Agent identifier	$\mathbf{R}^+$
:	Measure defined over agents	
$h^i$	Human capital	$:\mathbf{R}^+ \triangleleft \mathbf{R}^+$
$l$	Aggregate human capital stock	$\mathbf{R}^+$
$K^i$	Beauty	$(0,1)$
$0_q$	Weight on human capital in pizzazz	$> 0, q = m, f$
$p^i$	Own pizzazz	$> 0$
$p^j$	Spouse's pizzazz	$> 0$
$\bar{p}^j$	Lifetime minimum acceptable pizzazz for spouse	$> 0$
$A$	Genome	52-d vector
$a_j$	Allele in genome in location $j$	$\{0,1\}$
$\forall_j$	Weight on allele in location $j$ in production of $h$	$> 0$
$T$	Flynn effect parameter	$\geq 1$
$e^i$	Education/experience	$N(1, .25^2)$
$\varkappa$	Weight on Education/experience in production of $h$	$(0,1)$
$b^{iP}$	Number of siblings	$\mathbf{N}^+$
$2$	Weight on $ b^{iP} - 2 $ in production of $h$	$> 0$

Table A1 (contd.)

$\alpha$	Utility weight from number of children	$> 0$
$B$	Joy of marriage utility weight from spouse's pizzazz	$> 0$
$c_1^i$	Consumption as a young adult	$> 0$
$c_2^i$	Consumption as a older adult	$> 0$
$d^i$	Cost of raising a child	$> 0$
$w$	Economy-wide wage	$> 0$
$\exists$	Patience for consumption	$> 0$
$\cdot$	Marriage ( $\cdot = 1$ ) indicator	$\{0,1\}$
$a^i$	Assets saved for old-age consumption	$\geq 0$
$R$	Yield on savings	$\geq 0$
$D$	Scale factor on cost of children function	$> 0$
$r$	Marriage matching round index	$\mathbf{N}^+$
$\Delta$	Maximum number of marriage matching rounds	$\mathbf{N}^+$
$Y$	Aggregate output	$:\mathbf{R}^{+2} \square \mathbf{R}^+$
$K$	Aggregate physical capital stock	$> 0$
$A$	Scale factor in production	$> 0$
$N$	Number of young adults	$\geq 0$
$h$	Average human capital	$> 0$
$c^{ij}$	Indicator that $i$ loves $j$	$\{0,1\}$

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## Notes

1. The overlapping generations framework was introduced in the ecological model of Lesile (1945), and independently developed and applied to economic exchange by Samuelson (1958). The model was significantly extended to include production by Diamond (1965), and subsequently many others; see Azariadis (1993).
2. See Graefen (1998, 2000) for models of fertility in which agents explicitly maximize reproductive fitness.
3. Same-sex meetings impose no decisions for agents as friendship is not valued and homosexual unions are not part of the model.
4. Marriage matching under uncertainty, divorce, and remarriage are examined in a companion paper, Park & Zak (2001); see also Greenwood et al. (1999), Aiyagari et al. (2000), and Geddes & Zak (2002). On optimal separation, see Burdett & Coles (1999).
5. Finnish anthropologist Edvard Westermarck (1891) first identified the sexual aversion of siblings. Subsequent genetic analysis identified the biological basis for this behavior as the presence of lethal genes that all humans carry. On average, every individual has two lethal genes; if a particular location on the genome has a pair of lethal genes (i.e. one each from the father and mother), the fetus dies in utero or shortly after birth. Mating by siblings raises the probability of homozygous lethal genes in an offspring to 1 in 4, from 1 in 15 000 in the general population. This is known as 'inbreeding depression', and is also associated with semi-lethal genetic diseases such as hemophilia. Inbreeding depression is the presumed basis for incest taboos (Wolf 1995).
6. On market versus nonmarket labor supply choices for men and women, also see Grossbard-Shechtman (1984), Grossbard-Shechtman & Neuman (1988), and the survey in Weiss (1997).
7. Throughout this paper we use 'marriage' in its broad sense to denote a pair of agents who form a union and reproduce.
8. Hammermesh & Biddle (1994) show that people identified as more beautiful earn higher incomes. Because their sample is not representative, this finding may not generalize, so we ignore this issue in the present study. Nevertheless, it is easily included by permitting an agent's labor income to depend on pizzazz.
9. Other factors affecting mate choice include social and cultural factors, age of mate, chastity, religion, ambition, and love. There are all outside the model except for love, which we examine in Section 4.5.
10. These studies are consistent with biological research that has begun to identify the specific genes responsible for intelligence. See Plomin et al. (2000) and Brody (1992) on the genetic basis for intelligence.
11. A specific gene or genes could be modeled with its full set of base pairs computationally, but this would add little to the model and substantially reduce the number of experiments we would be able to run.
12. More precisely, *introns* which act as punctuation for genes are about 10% of the human genome, while the functions of *intergenic sequences* that are about 87% of the genome are currently largely unknown.
13. The code is written in the GAUSS programming language (a sample program is available upon request). Running on a Pentium III PC at 700 MHz, the base program, with 300 initial agents takes 8 hours to solve the model for 70 generations.
14. We ignore a host of other effects that impact recombination, such as maternal age, cell temperature, nutrition, the presence of chemicals or radiation, as well as chromosome structure as these are second-order effects.
15. If either location 10 or 11 mutates, the new gene pair become linked.
16. Lamarck (1809) argued that learned traits entered the germline and were passed down to children, a theory for which little evidence exists today. Rather, the genetics-environment feedback occurs through environmentally mediated 'regulator genes' that turn off and on 'structural genes' that code for proteins, affecting childhood development without passing through to the germline. Edelman (1992) and



- Gazzaniga (1992) apply the regulator genes model to explain intelligence and consciousness, though the molecular basis for this mechanism is just beginning to be discovered.
17. The full analytical dynamics of this model when the genome is a scalar are contained in Zak (2000).
  18. The sex of a couple's children is a 50–50 draw in the model but that there is no reason to expect a balanced sex ratio at any point in time.
  19. The approximation of the marriage matching rule is consistent with agents having limited information processing capacities, as has been shown by Herbert Simon (1997). Simon argues that humans use rules of thumb to approximate optima in complex problems; see also the discussion in Cosmides & Tooby (1995).
  20. For a related model with immigration, see Zak et al. (2002).
  21. We thank Lutz Hendricks for suggesting this representation of output.
  22. Evolutionary epistemology and its relationship to equilibrium are discussed in Zak & Denzau (2001). Note that the biological landscape is also smooth since there is a single selection criterion, sexual selection, without conflicting biological constraints; see Kauffman (1995) on genotype-landscape feedbacks.
  23. The Flynn effect essentially internalizes aggregate technological change as in Romer (1986, 1990) and Weitzman (1998).
  24. The calibration of  $\omega$  proceeds as follows: For any individual, the genetic draws  $a_j$ , and education  $e$  are random variables, with  $E\{a_j\} = \frac{1}{2}\forall j$ , and  $E\{e\} = 1$ . Thus,  $E\{\sum_{j=1}^{50} a_j a_j\} = \frac{75}{2}$ . When 60% of the population marries (U.S. Census Bureau 1999), the replacement fertility rate among married households is  $b = 3.3$ , which produces a total fertility rate (the average number of children born to women during their reproductive years) of 2.0 which is the population replacement rate absent childhood deaths.
  25. Negative correlations with base model output are observed for parameter changes in one direction for  $\gamma$ ,  $n_q$  (weight on beauty in pizzazz),  $\omega$  (Flynn effect), and  $D$  (cost of children scale factor). Examining these time series, one sees that this occurs primarily because output is trended in subsamples, even though the overall growth trend for each simulation is positive.
  26. Note that the economy-wide wage  $\omega$  does not change with the information revolution due to foreign capital flows, although labor income for agent  $i$ ,  $wh^i$  generally changes since  $h^i$  will change for most agents.
  27. Over long time intervals, subgroup inbreeding can lead to speciation where interbreeding between subgroups is no longer possible.
  28. On the genetic resistance to diseases, see the survey by Qureshi et al. (1999).
  29. Since the 52nd gene determines an agent's beauty, we use a standard rounding rule to include this factor in the immunity calculation. This is consistent with the constituents of beauty, especially body symmetry, signaling the ability to resist disease.
  30. An alternative specification changes mate preferences to be defined only over a select set of agents; since we seek to keep preferences fixed through every simulation, we do not take this tack.
  31. The assumption of costless matching of potential spouses is consistent with individuals who sort themselves regarding where to live, work, and play by pizzazz.
  32. Here we are talking about 'sexual love' as defined by Solomon (2001) and Singer (1984, 1994), or what Plato called *eros*.
  33. A similar stochastic draw for the quality of a match is used by Aiyagari et al. (2000).
  34. On the effects of diversity, also see Zak & Knack (2001).

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