The Medical Expansion, Life-Expectancy and Endogenous Directed Technical Change

Leon Huetsch[a] Dirk Krueger[b] Alexander Ludwig[c]

[a]University of Pennsylvania

[b]University of Pennsylvania, CEPR, CFS, NBER and Netspar

[c]Goethe University Frankfurt & ICIR, CEPR and Netspar

June 02, 2023

III Catalan Economic Society Congress

Barcelona

Motivation and Research Objective

- Facts: Three Phases of Health and Medical Development
  1. Life Expectancy at Age 20 flat until about 1840.
  2. Life Expectancy at Age 20 $\uparrow$ since about 1840.
  3. Emergence of Modern Health Sector ca. 1920-40: Investment $\uparrow$, Employment Share $\uparrow$, R&D Share $\uparrow$, Price of Health Goods $\uparrow$

Motivation and Research Objective

- Facts: Three Phases of Health and Medical Development
  1. Life Expectancy at Age 20 flat until about 1840.
  2. Life Expectancy at Age 20 $\uparrow$ since about 1840.
  3. Emergence of Modern Health Sector ca. 1920-40: Investment $\uparrow$, Employment Share $\uparrow$, R&D Share $\uparrow$, Price of Health Goods $\uparrow$
- Objective: Quantitative theory, predict future, evaluate policies

Motivation and Research Objective

- Facts: Three Phases of Health and Medical Development
  1. Life Expectancy at Age 20 flat until about 1840.
  2. Life Expectancy at Age 20 $\uparrow$ since about 1840.
  3. Emergence of Modern Health Sector ca. 1920-40: Investment $\uparrow$, Employment Share $\uparrow$, R&D Share $\uparrow$, Price of Health Goods $\uparrow$
- Objective: Quantitative theory, predict future, evaluate policies
- Building Blocks:
  1. Life Cycle: Diamond (1965)
  2. Endogenous Health Investment and Longevity: Grossman (1972)
  3. Endogenous Directed Technical Change: Aghion & Howitt (1992)

Modeling Approach

- Two-sector OLG model with endogenous technical change:
  - Households:
    - 2-period lived, endogenous survival in 2nd period.
    - Choices: consumption-savings, health spending.
    - Two health goods: basic hygiene & modern health services.

Modeling Approach

- Two-sector OLG model with endogenous technical change:
  - Households:
    - 2-period lived, endogenous survival in 2nd period.
    - Choices: consumption-savings, health spending.
    - Two health goods: basic hygiene & modern health services.
  - Firms:
    - Two sectors: health goods & final goods
    - Monopolistic competition in intermediate inputs $\Rightarrow$ Profits
    - Endogenous R&D: $\Rightarrow$ higher quality intermediates $\Rightarrow$ Profits.
    - Endogenous income growth through quality $\uparrow$ in both sectors.
- Quantitative implementation: Calibration to initial conditions, broad trends in US data.

Main Mechanism

- Phase 1: Low productivity & Low Income $\Rightarrow$ No Health Spending.

Main Mechanism

- Phase 1: Low productivity & Low Income $\Rightarrow$ No Health Spending.
- Phase 2: Productivity growth in basic goods sector $\Rightarrow$ Income $\uparrow$

  => Kick-off: Basic health spending $\uparrow$, life expectancy $\uparrow$.

Main Mechanism

- Phase 1: Low productivity & Low Income $\Rightarrow$ No Health Spending.
- Phase 2: Productivity growth in basic goods sector $\Rightarrow$ Income $\uparrow$

  $=>$ Kick-off: Basic health spending $\uparrow$, life expectancy $\uparrow$.
- Phase 3: Further income $\uparrow$, non-homotheticity in health spending:

  $=>$ Health spending $\uparrow$

  $=>$ Redirection of techn. progress to modern health sector.

  $=>$ Quality in modern health sector $\uparrow$, price of health goods $\uparrow$.

  $=>$ Convergence to interior BGP.

Results Today

- Stylized Facts
- Construction & calibration of simple, illustrative model.
- Calibrated model results: Model
  - replicates facts qualitatively
  - fits the data quantitatively
- Health Policy reforms: not yet today.

Related Literature

- Aghion-Howitt meets Grossman meets Diamond

  Diamond (1965), Grossman (1972), Aghion and Howitt (1992, 1998)

- Life expectancy, human capital & technological progress

  Cervellati & Sunde (2005), Hejkal, Ravikumar & Vandenbroucke (2022)

- Normative analyses of optimal health & R&D spending shares

  Hall and Jones (2007), Jones (2004, 2016)

- Reasons for growth of health spending

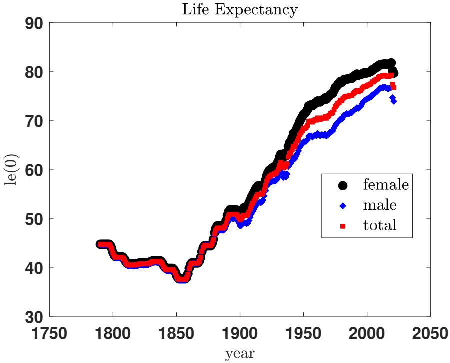
  Anderson et al. (2003), Fonseca et al. (2013), Zhao (2014), Hollingsworth et al. (2022)

- Health spending, R&D & feedback

  Frankovic and Kuhn (2018a,b), Böhm et al. (2018)

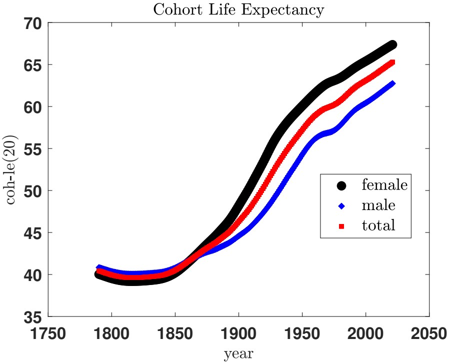
Outline

Remaining Life Expectancy at Age 0



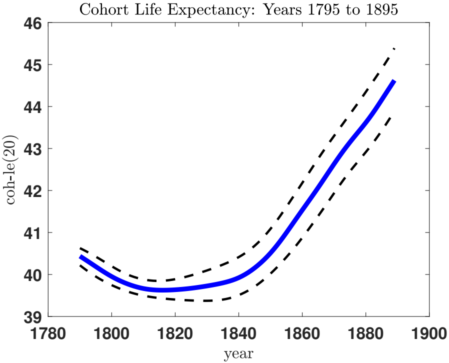
- Kick-off after 1850
- Source: Historical Life Expectancy Data (Haines, Hacker 2010), Human Life-Table Database, Human Mortality Database.

Remaining Cohort Life Expectancy at Age 20



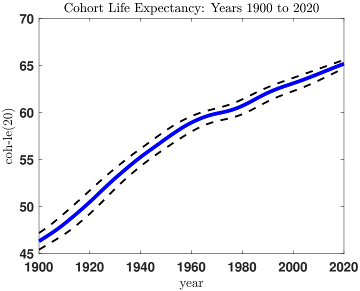
- Increased life expectancy at age 20: Takeoff about 1840.
- Source: Historical Life Expectancy Data (Haines, Hacker 2010), Human Life-Table Database, Human Mortality Database.

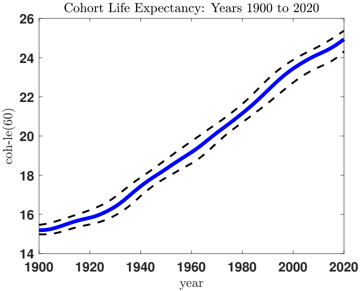
Cohort Life Expectancy: Kick-Off I



- Increased life expectancy at age 20: Takeoff ca. 1840.
- Source: Hacker (2010), Human Life-Table Database.

Cohort Life Expectancy: Kick-Off II

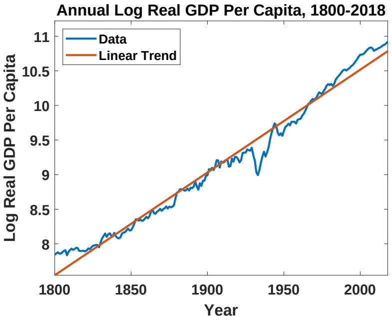




- Remaining cohort LE slightly
  - concave at age 20
  - convex at age 60: importance of modern health goods?

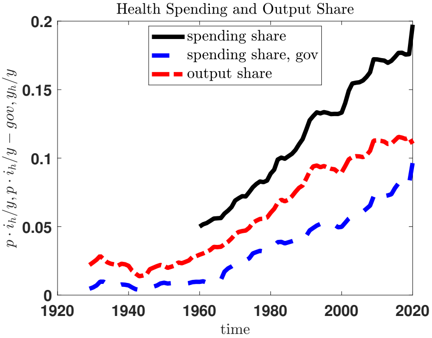
Source: Human Life-Table Database, Human Mortality Database.

Per Capita Income Growth



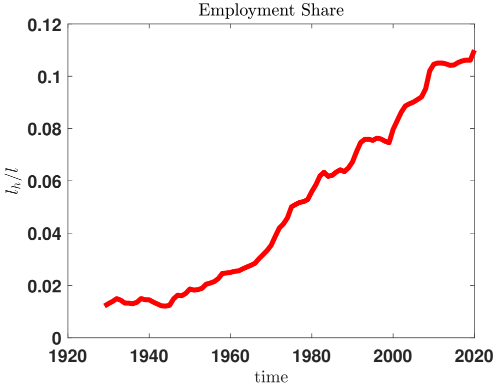
- Per capita income (log scale) started increasing in about 1820
- Constant growth at about 2% annually

Health Expenditure & Output Share



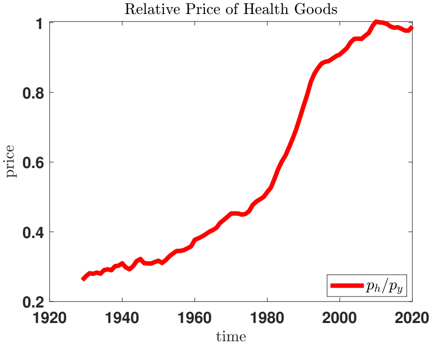
- Health expenditure share ↑
- Output share ↑ since WW.II
- Widespread use of penicillin since WW.II

Health Employment Share



- Employment share ↑ since WW.II.

Relative Price of Health Goods



- Increase of relative price of health goods & services
- Quality adjustment?

Outline

Model: Overview

Two-sector OLG model with endogenous technical change:

Model: Overview

Two-sector OLG model with endogenous technical change:

- Households:
  - 2-period lived, endogenous survival in 2nd period.
  - Consumption-savings choice
  - Demand: basic food & hygiene goods & modern health goods.

Model: Overview

Two-sector OLG model with endogenous technical change:

- Households:
  - 2-period lived, endogenous survival in 2nd period.
  - Consumption-savings choice
  - Demand: basic food & hygiene goods & modern health goods.
- Firms and Technology:
  - Two final goods sectors: modern health goods & generic consumption goods (includes hygiene & food).
  - Both sectors: continuum of intermediate inputs. Imperfect substitution & monopolistic competition $\Rightarrow$ Profits
  - Endogenous R&D: $\Rightarrow$ higher quality of intermediates $\Rightarrow$ Profits.
  - Endogenous income growth through quality $\uparrow$ in both sectors.

Model: Overview

Two-sector OLG model with endogenous technical change:

- Households:
  - 2-period lived, endogenous survival in 2nd period.
  - Consumption-savings choice
  - Demand: basic food & hygiene goods & modern health goods.
- Firms and Technology:
  - Two final goods sectors: modern health goods & generic consumption goods (includes hygiene & food).
  - Both sectors: continuum of intermediate inputs. Imperfect substitution & monopolistic competition $\Rightarrow$ Profits
  - Endogenous R&D: $\Rightarrow$ higher quality of intermediates $\Rightarrow$ Profits.
  - Endogenous income growth through quality $\uparrow$ in both sectors.
- SOE: interest rate $R_t = R$ exogenous, constant.

Households: Utility and Choices

- consumption-savings (c_{t+1}, s_t), health investment (i_t, i_{ht}, i_{ft}), given prices p_t, R.

Households: Utility and Choices

- consumption-savings (c_{t+1}, s_t), health investment (i_t, i_{ht}, i_{ft}), given prices p_t, R.
- Utility from old-age consumption and survival:

$$\psi(i_t)u(c_{t+1}) = \psi(i_t)\left(\frac{c_{t+1}^{1-\sigma}}{1-\sigma} + b\right)$$

- No suicide condition: b sufficiently large (required if $\sigma \geq 1$).

Households: Utility and Choices

- consumption-savings (c_{t+1}, s_t), health investment (i_t, i_{ht}, i_{ft}), given prices p_t, R.
- Utility from old-age consumption and survival:

$$\psi(i_t)u(c_{t+1}) = \psi(i_t)\left(\frac{c_{t+1}^{1-\sigma}}{1-\sigma} + b\right)$$

- No suicide condition: b sufficiently large (required if $\sigma \geq 1$).
- Survival probability increases in i_t:

$$\psi(i_t) = 1 - (1 + i_t)^{-\xi}.$$

Households: Utility and Choices

- consumption-savings (c_{t+1}, s_t), health investment (i_t, i_{ht}, i_{ft}), given prices p_t, R.
- Utility from old-age consumption and survival:

$$\psi(i_t)u(c_{t+1}) = \psi(i_t)\left(\frac{c_{t+1}^{1-\sigma}}{1-\sigma} + b\right)$$

- No suicide condition: b sufficiently large (required if $\sigma \geq 1$).
- Survival probability increases in i_t:

$$\psi(i_t) = 1 - (1 + i_t)^{-\xi}.$$

- Health investment quasi-linear in basic, modern health goods:

$$i_t = \eta i_{ht} + (\nu + i_{ft})^{\zeta}$$

- Note that $\psi'(i_{ht} = i_{ft} = 0) < \infty$ but $u'(c_{t+1} = 0) = \infty$.

Households: Utility and Choices

- consumption-savings (c_{t+1}, s_t), health investment (i_t, i_{ht}, i_{ft}), given prices p_t, R.
- Utility from old-age consumption and survival:

$$\psi(i_t)u(c_{t+1}) = \psi(i_t)\left(\frac{c_{t+1}^{1-\sigma}}{1-\sigma} + b\right)$$

- No suicide condition: b sufficiently large (required if $\sigma \geq 1$).
- Survival probability increases in i_t:

$$\psi(i_t) = 1 - (1 + i_t)^{-\xi}.$$

- Health investment quasi-linear in basic, modern health goods:

$$i_t = \eta i_{ht} + (\nu + i_{ft})^{\zeta}$$

- Note that $\psi'(i_{ht} = i_{ft} = 0) < \infty$ but $u'(c_{t+1} = 0) = \infty$.
- Budget constraints:

$$p_t i_{ht} + i_{ft} + s_t := e_t + s_t = w_t + T_t := x_t$$
$$c_{t+1} = Rs_t$$

Analysis of Household Problem: Three Phases

Suppose sequence of prices & cash at hand $\{p_t, x_t\}$ satisfy

$$x_{t+1} > x_t, p_{t+1} < p_t.$$

Analysis of Household Problem: Three Phases

Suppose sequence of prices & cash at hand $\{p_t, x_t\}$ satisfy

$$x_{t+1} > x_t, p_{t+1} < p_t.$$

Then there exist time thresholds $0 < T_1 < T_2 < \infty$ such that

1. Phase 1: $\forall t < T_1$: $i_t = i_{ft} = i_{ht} = 0$, $\psi(i_t) = \psi(0)$ & $c^o_{t+1} = Rx_t$.

Analysis of Household Problem: Three Phases

Suppose sequence of prices & cash at hand $\{p_t, x_t\}$ satisfy

$$x_{t+1} > x_t, p_{t+1} < p_t.$$

Then there exist time thresholds $0 < T_1 < T_2 < \infty$ such that

1. Phase 1: $\forall t < T_1$: $i_t = i_{ft} = i_{ht} = 0$, $\psi(i_t) = \psi(0)$ & $c^o_{t+1} = Rx_t$.
2. Phase 2: $\forall t \in [T_1, T_2)$: $i_t = i_{ft} > 0$, $i_{ht} = 0$ & $\psi(i_t) > \psi(0)$. Life expectancy $\uparrow$: better basic hygiene, no modern health sector.

Analysis of Household Problem: Three Phases

Suppose sequence of prices & cash at hand $\{p_t, x_t\}$ satisfy

$$x_{t+1} > x_t, p_{t+1} < p_t.$$

Then there exist time thresholds $0 < T_1 < T_2 < \infty$ such that

1. Phase 1: $\forall t < T_1$: $i_t = i_{ft} = i_{ht} = 0$, $\psi(i_t) = \psi(0)$ & $c^o_{t+1} = Rx_t$.
2. Phase 2: $\forall t \in [T_1, T_2)$: $i_t = i_{ft} > 0$, $i_{ht} = 0$ & $\psi(i_t) > \psi(0)$. Life expectancy $\uparrow$: better basic hygiene, no modern health sector.
3. Phase 3: For all $t \geq T_2$ we have $i_{ft} > 0$ & $i_{ht} > 0$ as well as $\psi(i_t) > \psi(0)$. Life expectancy $\uparrow$, also modern health goods $\uparrow$.

Analysis of Household Problem: Three Phases

Suppose sequence of prices & cash at hand $\{p_t, x_t\}$ satisfy

$$x_{t+1} > x_t, p_{t+1} < p_t.$$

Then there exist time thresholds $0 < T_1 < T_2 < \infty$ such that

1. Phase 1: $\forall t < T_1$: $i_t = i_{ft} = i_{ht} = 0$, $\psi(i_t) = \psi(0)$ & $c^o_{t+1} = Rx_t$.
2. Phase 2: $\forall t \in [T_1, T_2)$: $i_t = i_{ft} > 0$, $i_{ht} = 0$ & $\psi(i_t) > \psi(0)$. Life expectancy $\uparrow$: better basic hygiene, no modern health sector.
3. Phase 3: For all $t \geq T_2$ we have $i_{ft} > 0$ & $i_{ht} > 0$ as well as $\psi(i_t) > \psi(0)$. Life expectancy $\uparrow$, also modern health goods $\uparrow$.
4. BGP w/ constant $\frac{e}{x} = \frac{p \cdot i_h}{x} > 0$, $\frac{s}{x} > 0$, $\frac{c}{x} > 0$ & $p > 0$.

Production Side: Final Goods Production Firms

- Perfectly competitive final goods producers with CRTS technology in both sectors $j \in \{f, h\}$:

$$y_{jt} = \left(\int_0^1 q_{jit}^{1-\alpha} y_{jit}^{\alpha} \right) l_{jt}^{1-\alpha}$$

- Firms take as given: quality q_{jit}, prices p_{jit}, p_{jt}.
- Choices: y_{jt}, l_{jt}, y_{jit}

Production Side: Final Goods Production Firms

- Perfectly competitive final goods producers with CRTS technology in both sectors $j \in \{f, h\}$:

$$y_{jt} = \left(\int_0^1 q_{jit}^{1-\alpha} y_{jit}^{\alpha} \right) l_{jt}^{1-\alpha}$$

- Firms take as given: quality q_{jit}, prices p_{jit}, p_{jt}.
- Choices: y_{jt}, l_{jt}, y_{jit}
- FOC's for y_{jit} delivers inverse demand function for intermediates:

$$p_{jit} = \alpha p_{jt} \left(\frac{q_{jit} l_{jt}}{y_{jit}} \right)^{1-\alpha}$$

Intermediate Inputs: Monopolistic Competition

- Each variety $i \in [0, 1]$ is produced by a monopolist.
- Production function: $y_{jit} = k_{jit}$, full depreciation of capital k_{jit}.
- Firms take as given: inverse demand function & R.

Intermediate Inputs: Monopolistic Competition

- Each variety $i \in [0,1]$ is produced by a monopolist.
- Production function: $y_{jit} = k_{jit}$, full depreciation of capital k_{jit}.
- Firms take as given: inverse demand function & R.
- Profit maximization:

$$\pi_{jit} = \max_{k_{jit}} \left\{ \left[p_{jt} \alpha q_{jit}^{1-\alpha} k_{jit}^{\alpha-1} l_{jt}^{1-\alpha} \right] k_{jit} - R k_{jit} \right\}$$

Intermediate Inputs: Monopolistic Competition

- Each variety $i \in [0,1]$ is produced by a monopolist.
- Production function: $y_{jit} = k_{jit}$, full depreciation of capital k_{jit}.
- Firms take as given: inverse demand function & R.
- Profit maximization:

$$\pi_{jit} = \max_{k_{jit}} \left\{ \left[p_{jt} \alpha q_{jit}^{1-\alpha} k_{jit}^{\alpha-1} l_{jt}^{1-\alpha} \right] k_{jit} - R k_{jit} \right\}$$

- Solution: constant markup over marginal cost R, positive profits:

$$p_{jit} = \frac{1}{\alpha} R > R, \quad \pi_{jit} = \frac{1-\alpha}{\alpha} R k_{jit} > 0$$

Firms: Aggregating the Production Sector

- From intermediate goods producers' FOC: For all $i \in [0, 1]$,

$$\frac{k_{jit}}{q_{jit}} = \frac{k_{jt}}{q_{jt}},$$

where $q_{jt} = \int_0^1 q_{jit} di$ & $k_{jt} = \int_0^1 k_{jit} di$.

Firms: Aggregating the Production Sector

- From intermediate goods producers' FOC: For all $i \in [0, 1]$,

$$\frac{k_{jit}}{q_{jit}} = \frac{k_{jt}}{q_{jt}},$$

  where $q_{jt} = \int_0^1 q_{jit} di$ & $k_{jt} = \int_0^1 k_{jit} di$.

- Aggregation in each sector:

$$y_{jt} = k_{jt}^{\alpha} \left(q_{jt} l_{jt}\right)^{1-\alpha}$$

- Distribution of income:

$$p_{jt} y_{jt} = \left[(1-\alpha) + \alpha^2 + \alpha(1-\alpha)\right] p_{jt} y_{jt} = w_t l_{jt} + R k_{jt} + \pi_{jt}$$

R&D Production & Technological Progress

- R&D entrepreneur per variety i: resources z_{jit} on innovation.
- Probability of successful innovation:

$$\phi(z_{jit}; l_{jt}, q_{jit-1}) = \min\left[\frac{\varphi}{l_{jt}}\left(\frac{z_{jit}}{\lambda q_{jit-1}}\right)^{\gamma}, 1\right]$$

- Successful innovation: quality improvement $\lambda > 1$ so that $q_{jit} = \lambda q_{jit-1}$.
- Successful innovator: one period monopolist for i: Profits π_{jit}.

R&D Production & Technological Progress

- R&D entrepreneur per variety i: resources z_{jit} on innovation.
- Probability of successful innovation:

$$\phi(z_{jit}; l_{jt}, q_{jit-1}) = \min \left[\frac{\varphi}{l_{jt}} \left(\frac{z_{jit}}{\lambda q_{jit-1}} \right)^{\gamma}, 1 \right]$$

- Successful innovation: quality improvement $\lambda > 1$ so that $q_{jit} = \lambda q_{jit-1}$.
- Successful innovator: one period monopolist for i: Profits π_{jit}.
- R&D entrepreneur's problem:

$$\max_{z_{jit}} \left\{ \pi_{jit} \cdot \phi(z_{jit}; l_{jt}, q_{jit-1}) - z_{jit} \right\}$$

Solution $z_{jit} = \Phi(R, p_{jt}, l_{jt}) \lambda q_{jit-1}$.

R&D Production & Technological Progress

- R&D entrepreneur per variety i: resources z_{jit} on innovation.
- Probability of successful innovation:

$$\phi(z_{jit}; l_{jt}, q_{jit-1}) = \min\left[\frac{\varphi}{l_{jt}}\left(\frac{z_{jit}}{\lambda q_{jit-1}}\right)^{\gamma}, 1\right]$$

- Successful innovation: quality improvement $\lambda > 1$ so that $q_{jit} = \lambda q_{jit-1}$.
- Successful innovator: one period monopolist for i: Profits π_{jit}.
- R&D entrepreneur's problem:

$$\max_{z_{jit}} \left\{\pi_{jit} \cdot \phi(z_{jit}; l_{jt}, q_{jit-1}) - z_{jit}\right\}$$

  Solution $z_{jit} = \Phi(R, p_{jt}, l_{jt})\lambda q_{jit-1}$.
- Varieties i w/ unsuccessful innovations: quality $q_{jit} = q_{jit-1}$, randomly selected entrepreneur eats profits π_{jit}.

Firms: Aggregation of R&D & Economic Growth

- Since $\frac{z_{jit}}{\lambda q_{jit-1}} = \Phi(R, p_{jt}, l_{jt})$ constant across i:

$$\mu_{jt} = \frac{\varphi}{l_{jt}} \left(\frac{z_{jit}}{\lambda q_{jit-1}} \right)^{\gamma} = \frac{\varphi}{l_{jt}} \left(\Phi(R, p_{jt}, l_{jt}) \right)^{\gamma}$$

Firms: Aggregation of R&D & Economic Growth

- Since $\frac{z_{jit}}{\lambda q_{jit-1}} = \Phi(R, p_{jt}, l_{jt})$ constant across i:

$$\mu_{jt} = \frac{\varphi}{l_{jt}} \left(\frac{z_{jit}}{\lambda q_{jit-1}} \right)^{\gamma} = \frac{\varphi}{l_{jt}} \left(\Phi(R, p_{jt}, l_{jt}) \right)^{\gamma}$$

- Quality improvements as engine of growth:

$$q_{jt} = \mu_{jt} \lambda q_{jt-1} + (1 - \mu_{jt}) q_{jt-1}$$

- Growth rate in sector j:

$$g_{jt} = \frac{q_{jt}}{q_{jt-1}} = 1 + (\lambda - 1)\mu_{jt}.$$

Price & Quality of Health Goods

- Good f is the numeraire: $p_{ft} = 1$ for all t.
- Relative price of health goods per health efficiency unit i_{ht}:

$$p_{ht} =: p_t = \left(\frac{q_{ft}}{q_{ht}}\right)^{1-\alpha}$$

- Relative price, quality adjustment: $p_t \frac{q_{ht}}{q_{ft}}$

Balanced Growth Path (BGP) and Transition

- Interior BGP: quality (q_{ft}, q_{ht}), x_t, w_t, T_t grow at rate g.
- Constant prices $R, p_t = p$. Constant shares:

$$\frac{e_t}{x_t} = \frac{p_t i_{ht} + i_{ft}}{x_t} = \frac{p_t i_{ht}}{x_t} = \vartheta, \frac{s_t}{x_t} = 1 - \vartheta, \frac{c_{t+1}}{x_t} = R(1 - \vartheta)$$

- BGP with interior share $\vartheta = \frac{e}{x} \in (0, 1)$ exists iff $\sigma = 1 + \xi$.

Balanced Growth Path (BGP) and Transition

- Interior BGP: quality (q_{ft}, q_{ht}), x_t, w_t, T_t grow at rate g.
- Constant prices $R, p_t = p$. Constant shares:

$$\frac{e_t}{x_t} = \frac{p_t i_{ht} + i_{ft}}{x_t} = \frac{p_t i_{ht}}{x_t} = \vartheta, \frac{s_t}{x_t} = 1 - \vartheta, \frac{c_{t+1}}{x_t} = R(1 - \vartheta)$$

- BGP with interior share $\vartheta = \frac{e}{x} \in (0, 1)$ exists iff $\sigma = 1 + \xi$.
- Why? FOC w.r.t. $\vartheta_t = \frac{e_t}{x_t}$ equates marginal benefit of health spending (longer life) to cost (reduced consumption):

$$\max_{\vartheta_t} \left(1 - \frac{1}{(1 + i_t(\vartheta_t x_t))^{\xi}}\right) \left(\frac{(Rx_t(1 - \vartheta_t))^{1-\sigma}}{1 - \sigma} + b\right)$$

- For (c_{t+1}, e_t) to grow at same rate: $\sigma = 1 + \xi$.

Transition to BGP

- State of the economy $(q_{ht-1}, q_{ft-1}, n_t, s_{t-1})$
- Given state (& $R_t = R$): static equilibrium, determine p_t (or $\frac{l_{ft}}{l_{ht}}$).

Transition to BGP

- State of the economy $(q_{ht-1}, q_{ft-1}, n_t, s_{t-1})$
- Given state (& $R_t = R$): static equilibrium, determine p_t (or $\frac{l_{ft}}{l_{ht}}$).
- Assumption $\sigma = 2$, thus $\xi = 1$: closed-form for interior $\vartheta_t \Rightarrow$

  demand for health goods $\Rightarrow$ update of state $\Rightarrow (n_{t+1}, s_t)$.

Transition to BGP

- State of the economy $(q_{ht-1}, q_{ft-1}, n_t, s_{t-1})$
- Given state (& $R_t = R$): static equilibrium, determine p_t (or $\frac{l_{ft}}{l_{ht}}$).
- Assumption $\sigma = 2$, thus $\xi = 1$: closed-form for interior $\vartheta_t \Rightarrow$

  demand for health goods $\Rightarrow$ update of state $\Rightarrow (n_{t+1}, s_t)$.
- Relative price p_t determines $l_{ft}, l_{ht}, \mu_{ft}, \mu_{ht}$.
- Update of state: $\Rightarrow (q_{ht}, q_{ft})$.

Extensions for Quantitative Analysis

- Labor intensive health sector: $\alpha_h = 0.22, \alpha_f = 0.33$. (Acemoglu and Guerrieri 2008).
- Differential improvement factors: λ_j
- Sector-specific parameters: plausible size of both sectors

Extensions for Quantitative Analysis

- Labor intensive health sector: $\alpha_h = 0.22, \alpha_f = 0.33$. (Acemoglu and Guerrieri 2008).
- Differential improvement factors: λ_j
- Sector-specific parameters: plausible size of both sectors
- Key optimality conditions (& requirement for BGP) qualitatively unchanged (still need $\Rightarrow \sigma = 1 + \xi$). Currently $\sigma = 2$.

Outline

Thought Experiment

- Basic Question: Can the model replicate basic empirical facts?
  - Life expectancy at age 20
  - Existence & size of modern health sector
  - Relative price of health goods

Thought Experiment

- Basic Question: Can the model replicate basic empirical facts?
  - Life expectancy at age 20
  - Existence & size of modern health sector
  - Relative price of health goods
- 40 year model periods: young 20-59, old 59-100
- Six periods: 1820 (phase 1), 1860, 1900 (phase 2),

  1940, 1980, 2020 (phase 3).
- Future Question: (Optimal) role of government in health R&D.

Calibration Strategy

- Value of life b: kick-off of basic health good spending
- Quality gap: kick-off of modern health good spending
- IES $1/\sigma = 0.5$ standard. $\Rightarrow \xi = 1$.
- Minimum survival probability: adult remaining life expectancy of 40.2 years in 1790.

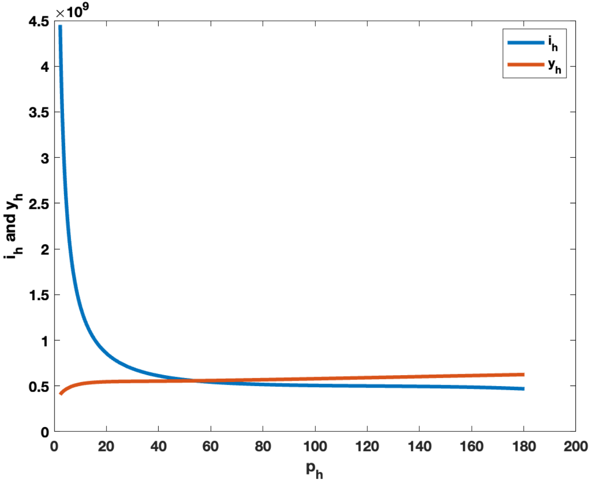
Calibration Strategy

- Value of life b: kick-off of basic health good spending
- Quality gap: kick-off of modern health good spending
- IES $1/\sigma = 0.5$ standard. $\Rightarrow \xi = 1$.
- Minimum survival probability: adult remaining life expectancy of 40.2 years in 1790.
- Growth factor λ_f: overall GDP growth
- Growth factor λ_h: relative growth of modern health sector
- Innovation parameters γ, φ: relative R&D spending (not yet).

Parameters

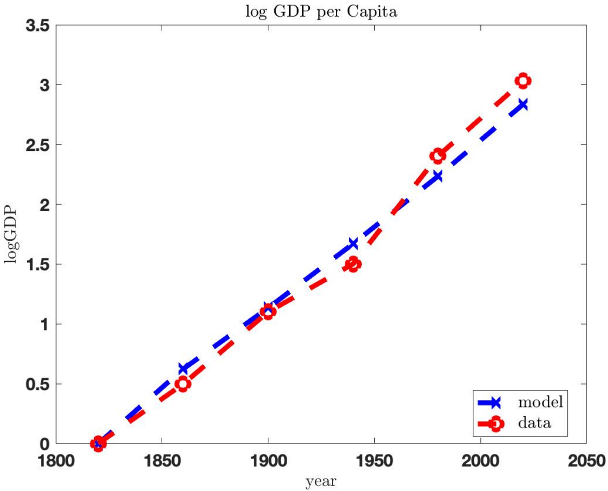
SOE	
Rate of return R-1	1.5 ($\approx$ 1 % annually)
Initial Condition	
Quality gap $\frac{q_{h0}}{q_{f0}}$	0.027192
Households	
Value of Life b	7.03
IES $1/\sigma$	0.5
Tail parameter, survival function ξ	1
Min. surv. prob. at i = 0, ν^{ζ}	0.020669
Scale parameter, modern health investment η	5
Firms	
Capital elasticities [$\alpha_{f,1940}$, $\alpha_{f,2020}$, $\alpha_{h,1940}$, $\alpha_{h,2020}$]	[0.33,0.33,0.025,0.2]
Growth factor [λ_f , λ_h]	[115,3]
Innovation probability, curvature [γ_f , γ_h]	[0.5,0.5]
Innovation probability, scale [φ_f , φ_h]	[0.5,0.5]

Determination of BGP: Demand & Supply



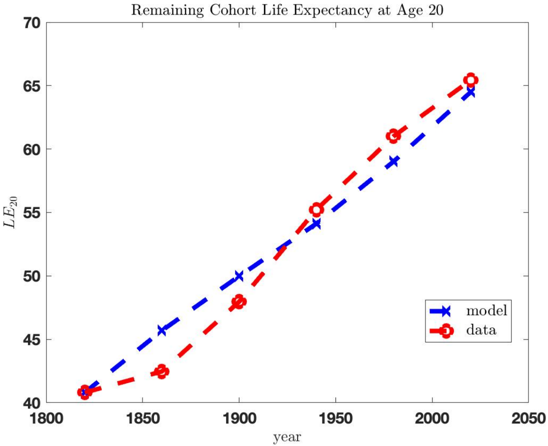
- Unique BGP equilibrium

Comparison to Data: Log GDP per Capita



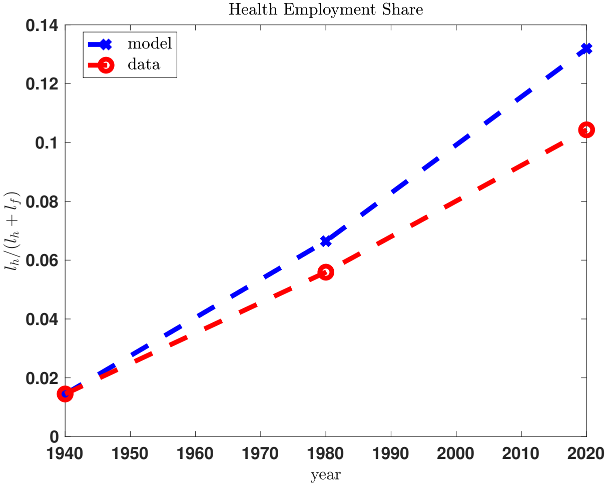
- Comparison looks good (easy to match)

Transition: Life Expectancy at Age 20



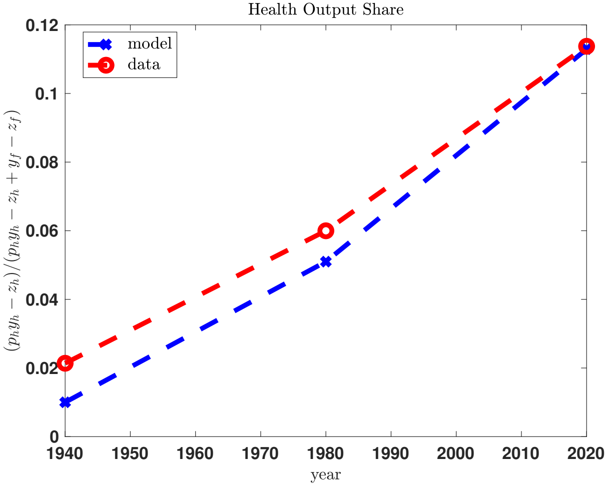
- Constant LE prior to kick-off, then increasing.

Comparison to Data: Health Employment Share



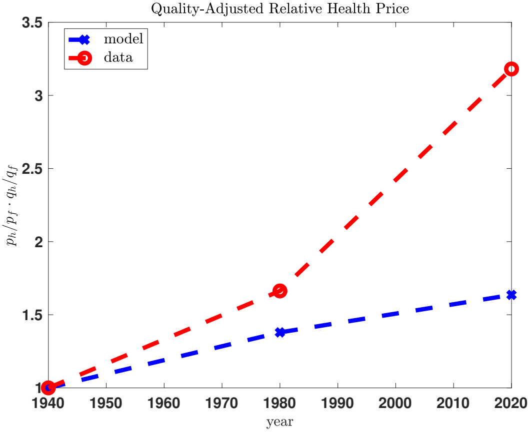
- Matches increase qualitatively, but too rapid quantitatively

Comparison to Data: Health Output Share



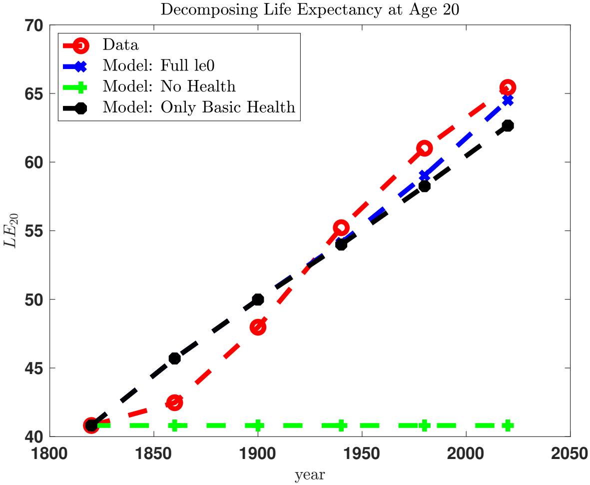
- Matches increase qualitatively, but too rapid quantitatively

Comparison to Data: Price of Health Goods



- $p\frac{q_{ht}}{q_{ft}}$: Right qualitatively, misses acceleration of prices in data.

Decomposition of Life Expectancy at Age 20



- Growing contribution of modern health after 2^{nd} kickoff

Outline

Conclusion: What We Have

Endogenous growth model with a health sector generating...

- ... kick-off of adult life expectancy and (later) modern medicine
- ... positive trend of health spending share
- ... positive trend of health employment, R&D spending shares
- ... increasing relative price of health
- ....continuously increasing life-expectancy in 20-th century

Conclusion: Next Step and Outlook

- Quantitative evaluation: reforms to health care & public R&D policies
- Model elements:
  - Life Cycle Model
  - Explicit model of health accumulation and frailty
  - consumption, savings, health investment, & endogenous retirement
  - household heterogeneity in life expectancy
  - Private & social insurance: health insurance & social security