

Automation, Learning, and Career Dynamics

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MOTIVATION: TWO VIEWS OF AI AND HUMAN CAPITAL

Pessimistic view

- AI is a **substitute** for entry-level white-collar workers (bottom rungs of the job ladder)

“AI could wipe out half of all entry-level white-collar jobs within the next one to five years” — Dario Amodei, Anthropic 2025

- Fewer entry positions → less on-the-job learning → less productive future managers
- BCG (2026): 53% of business leaders cite slower development of junior talent as a concern

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Optimistic view

- AI is a **complement** for senior workers who create new products and ideas (higher rungs) → job creation

“...an opportunity to create new industries, create brand new jobs” — Jensen Huang, Nvidia 2026

- AI eliminates menial tasks → more time on activities that build knowledge
- McKinsey (2026): “winning organizations won’t just automate faster – they’ll learn faster”

How does such technology (AI) affect human capital accumulation with endogenous learning on the job?

- We develop an equilibrium model of human capital accumulation with endogenous learning, automation, and frontier choice

What we find:

- Unique equilibrium but multiple steady states with high and low learning on the job
- As the technology becomes more productive, two opposing forces emerge:
 - more automation hinders learning on the job (the pessimistic view)
 - task frontier expands and facilitates more learning (the optimistic view)
- For low levels of productivity, second effect dominates and human capital expands
- For very high levels of productivity, first effect dominates but is “close” to efficient

Model

- **Time:** continuous, indexed by $t \geq 0$
- **Agents:** a unit measure of individuals and a representative (atomistic) firm
- **Worker Heterogeneity:** differences in human capital x due solely to life cycle reasons
- **Perpetual youth model:** individuals die at rate χ and are born with $x = 1$
- Individuals accumulate human capital through **learning-by-doing**
- **Worker Decision:** when to transition from worker to manager (career ladder)
- **Firm Decisions:** hire workers and managers, create new tasks and potentially automate existing tasks

- **Technology for production:** $y(t) = \int_0^{f(t)} y(\tau, t)^{1-\eta^{-1}} d\tau$ with $\eta > 1$

$$y(\tau, t) = \int x dN_e(x, t; \tau) + z(\tau)a_e(\tau, t) \quad [\text{perfect substitutes}]$$

- η : governs diminishing returns of production (profitability of new task)
- τ : tasks that are produced
- $f(t)$: task frontier (endogenous, defined on next slide)
- x : human capital of workers
- $a_e(\tau, t)$: technology input for production (has exogenous price q)
- $z(\tau) = e^{-\varepsilon\tau}$ is task-specific productivity

Note: tasks ordered such that $z(\tau)$ is decreasing (existence of automation cutoff $\tau^*(t) \in [0, f(t)]$)

- **Technology for frontier:**

$$f(t) = \min \left\{ \bar{\tau} \left[\psi^{\omega^{-1}} a_m(t)^{1-\omega^{-1}} + (1 - \psi)^{\omega^{-1}} s(t)^{1-\omega^{-1}} \right]^{\frac{1}{1-\omega^{-1}}}, \bar{f} \right\}$$

- $\bar{f}$ maximum number of tasks (bounded growth of human capital)
- $a_m(t)$: technology used in producing the frontier (also has exogenous price q)
- $s(t) := \int h(x) dN_m(x, t)$: managerial input
 - $h(x)$: human capital of managers
 - $dN_m(x, t)$: the number of managers
- $\bar{\tau}$: exogenous productivity in production of the task frontier,
- ψ : weight on technology in producing task frontier
- ω : complementarity between managers and technology in producing task frontier
- Interested in $\omega < 1$: **technology and managers are complements**

- **Preferences:** $U_h(\{c\}) = \mathbb{E} \left[\int_0^\infty e^{-(\rho+\chi)t} c_{t+h,h} dt \right]$

- **Occupation choice:** $l(x, t) : [1, \infty) \rightarrow \{e, m\}$

- Income of a worker executing a task: $w_e(t) x$

- Income of a manager: $w_m(t) x^\xi$ with $\xi > 1$

- **Household problem:** choose $\mathcal{A}_h := \{l(x, t)\}_{t \geq 0}$:

$$(\rho + \chi) V(x, t) = \max \left\{ \underbrace{w_e(t) x + \varphi_e(t) x \partial_x V(x, t)}_{l(x, t)=e}, \underbrace{w_m(t) x^\xi + \varphi_m(t) x \partial_x V(x, t)}_{l(x, t)=m} \right\} + \Pi(t) + \partial_t V(x, t)$$

- **Worker human capital accumulation:**

$$\dot{x}(t) = \varphi(t) x(t)$$

- $\varphi(t) = g(\text{tasks done by workers}) \equiv \delta(f(t) - \tau^*(t)) \leq \varphi^{\max} \equiv \delta \bar{f}$
- δ : Governs the speed of learning
- τ^* : Cutoff for tasks that are automated
- Assume no human capital growth of managers (today)
- Assume δ does not change with q (today); having δ increase as q falls similar to q expanding the frontier

⇒ **Workers accumulate human capital based on the measure of non-automated tasks they perform (individual learning-by-doing)**

PLANNER'S PROBLEM: FIRST BEST

- Firm chooses an allocation $\mathcal{A}_f(t) := \{N_e(x, t; \tau), N_m(x, t), s(t), \tau^*(t), a_e(\tau, t), a_m(t)\}$ to solve:

$$\Pi(t) = \max_{\mathcal{A}_f(t)} \left\{ \underbrace{\int_0^{\tau^*(t)} \left[(z(\tau) a_e(\tau, t))^{1-\eta} - p_a(t) a_e(\tau, t) \right] d\tau}_{\text{profits from automated tasks}} + \underbrace{\int_{\tau^*(t)}^{f(t)} \left[x(\tau, t)^{1-\eta} - w_e(t) x(\tau, t) \right] d\tau}_{\text{profits from worker tasks}} - w_m(t) s(t) - p_a(t) a_m(t) \right\}$$

subject to $x(\tau, t) := \int x dN_e(x, t; \tau)$, $s(t) = \int h(x) dN_m(x, t)$, $f(t)$ and $\varphi = \delta(f(t) - \tau^*(t))$

- Note:** Technology good produced from the final good at constant returns $\Rightarrow p_a(t) = q$

DECENTRALIZED PROBLEM: FIRM DOES NOT INTERNALIZE AUTOMATION AND FRONTIER DECISIONS ON LEARNING

- Firm chooses an allocation $\mathcal{A}_f(t) := \{N_e(x, t; \tau), N_m(x, t), s(t), \tau^*(t), a_e(\tau, t), a_m(t)\}$ to solve:

$$\Pi(t) = \max_{\mathcal{A}_f(t)} \left\{ \underbrace{\int_0^{\tau^*(t)} \left[(z(\tau) a_e(\tau, t))^{1-\eta} - p_a(t) a_e(\tau, t) \right] d\tau}_{\text{profits from automated tasks}} + \underbrace{\int_{\tau^*(t)}^{f(t)} \left[x(\tau, t)^{1-\eta} - w_e(t) x(\tau, t) \right] d\tau}_{\text{profits from worker tasks}} - w_m(t) s(t) - p_a(t) a_m(t) \right\}$$

subject to $x(\tau, t) := \int x dN_e(x, t; \tau)$, $s(t) = \int h(x) dN_m(x, t)$, and $f(t)$

- Externality:** Learning is general and firms have limited commitment
 $\Rightarrow$ firms do not internalize that τ^* and f determine φ and thus future human capital

KEY EQUATIONS: STATIONARY EQUILIBRIA $\Rightarrow$ WORKER WAGES AS A FUNCTION OF q

- Optimal automation threshold $[\tau^*]$:

$$\tau^* \equiv \frac{1}{\varepsilon} \ln \frac{w_e}{q} \quad (0 < \tau^* < f)$$

- Optimal Frontier Choice $[f]$:

$$\underbrace{\eta^{-1} \left(\frac{\min\{q e^{\varepsilon f}, w_e\}}{1 - \eta^{-1}} \right)^{1-\eta}}_{\text{Marginal value (profit of new task)}} = \underbrace{\frac{1}{\bar{\tau}} [\psi q^{1-\omega} + (1 - \psi) w_m^{1-\omega}]}_{\text{Marginal cost}}^{\frac{1}{1-\omega}}$$

- Equilibrium in market for workers: Labor Demand = Labor Supply

$$\int_{\tau^*}^f \left(\frac{w_e(\varphi, q)}{1 - \eta^{-1}} \right)^{-\eta} d\tau = \int_1^{x^*} x dN(x)$$

- Build up the model in two simplified models before moving on to full model:
 1. Endogenous learning, exogenous frontier
 2. + Endogenous frontier ($\psi = 1$: no managers in frontier production)
 3. Full Model (probably not today)
- Note: in the first two examples there are no managers: all individuals are workers
- Key simplification in first two models:

Equilibrium dynamics are summarized by average human capital: $X(t) := \int x dN(x, t)$

Simplified Model 1:

Automation and *Endogenous* Learning
(No Career Choice/No Frontier Expansion)

- **Parameter Restrictions**
 - **Endogenous learning rate:** $\varphi(t) = \delta (\bar{f} - \tau^*(t))$
 - Exogenous frontier ($f = \bar{f}$); no career choice (everybody works)
 - Start by analyzing the decentralized model (to build intuition)

- Human capital dynamics:

$$\dot{X}(t) = \varphi(t)X(t) - \chi(X(t) - 1) \implies X_{ss} = \frac{\chi}{\chi - \varphi}$$

- Steady state in terms of φ :** market clearing with $\varphi = \delta(\bar{f} - \tau^*) \implies \tau^* = \bar{f} - \varphi/\delta$ and $w_e(\varphi, q) = qe^{\varepsilon\tau^*}$ (pinned down by automation threshold):

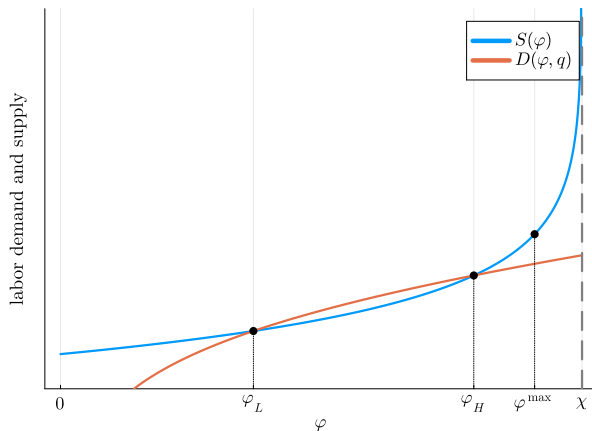
$$\underbrace{\frac{\varphi}{\delta} \left(\frac{w_e(\varphi, q)}{1 - \eta^{-1}} \right)^{-\eta}}_{\text{Human Capital (HC) Demand: } D(\varphi, q)} = \underbrace{\frac{\chi}{\chi - \varphi}}_{\text{Human Capital (HC) Supply: } S(\varphi)}$$

No-automation corner: $\varphi = \delta\bar{f}$ is a steady state whenever $D(\delta\bar{f}, q) \leq S(\delta\bar{f})$

SHAPE OF THE HUMAN CAPITAL DEMAND AND SUPPLY CURVES

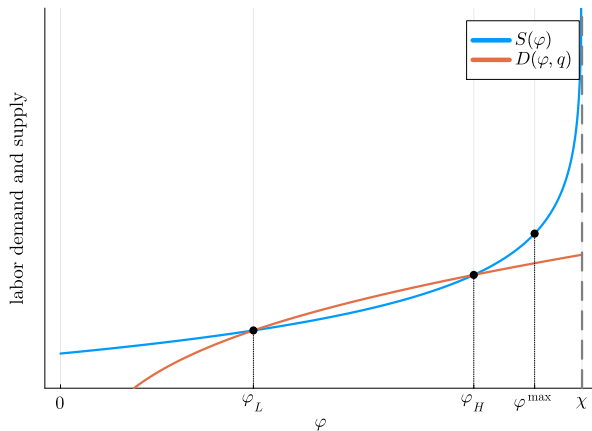
$$\underbrace{\frac{\varphi}{\delta} \left(\frac{w_e(\varphi, q)}{1 - \eta^{-1}} \right)^{-\eta}}_{\text{Human Capital (HC) Demand: } D(\varphi, q)} = \underbrace{\frac{\chi}{\chi - \varphi}}_{\text{Human Capital (HC) Supply: } S(\varphi)}$$

- **Given q , worker wages are decreasing in φ :** $w_e(\varphi, q) = qe^{\varepsilon\tau^*} = qe^{\varepsilon\bar{f}}e^{-\varepsilon\varphi/\delta}$
 - Sustaining higher learning and lower automation threshold requires lower wage, which raises labor demand
- **Both HC demand and supply increase with human capital accumulation:**
 - $\varphi = 0$: $D(\varphi, q) = 0$ and $S(\varphi) > 0$
 - $\varphi \rightarrow \chi$: $D(\varphi, q)$ is finite and $S(\varphi) \rightarrow \infty$

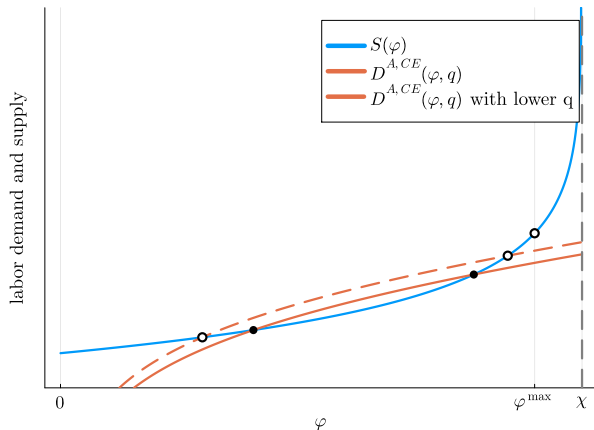


- **Two interior steady states:** $D(\varphi_L, q) = S(\varphi_L)$ (low-learning) and $D(\varphi_H, q) = S(\varphi_H)$ (high-learning)
- **Third steady state** at the bounded frontier ($\varphi^{\max} = \delta \bar{f}$)

ECONOMICS OF MULTIPLICITY: HC DEMAND AND HC SUPPLY



- **Low** $\varphi \rightarrow$ low labor supply $\rightarrow$ high wages $\rightarrow$ high automation $\rightarrow$ low learning $\rightarrow$...
- **High** $\varphi \rightarrow$ high labor supply $\rightarrow$ low wages $\rightarrow$ low automation $\rightarrow$ high learning $\rightarrow$...



- A decline in q will cause worker wages to fall $\Rightarrow$ labor demand (in φ space) shifts up
- Interior steady states **move apart**: $\varphi_L \downarrow$ and $\varphi_H \uparrow$ (difference mediated by $\frac{d \ln w_e(\varphi(q), q)}{d \ln q}$)

- **Out of steady state**, market clearing at each instant delivers a **unique** learning rate:

$$D(\varphi(t), q) = X(t) \text{ [Fixed]} \implies \varphi(t) = \varphi(X(t), q), \text{ increasing in } X(t) \text{ and } q$$

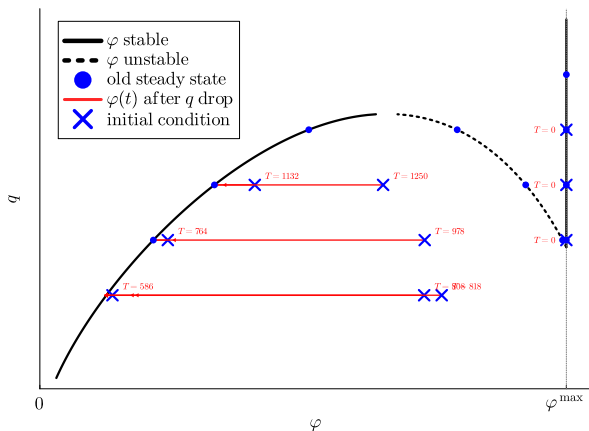
- **Dynamics of the state:** $\dot{X}(t) = F(X(t), q) \equiv \varphi(X(t), q)X(t) - \chi(X(t) - 1)$
- **Stability:** a steady state is stable iff $F_1(X_{ss}, q) < 0$
 - Stable steady states attract; unstable ones separate their **basins of attraction**
- **Comparative statics at any stable steady state:**

$$\text{sign}[X'_{ss}(q)] = \text{sign}[\partial_q \varphi]$$

$\implies$ Here $\partial_q \varphi > 0$:

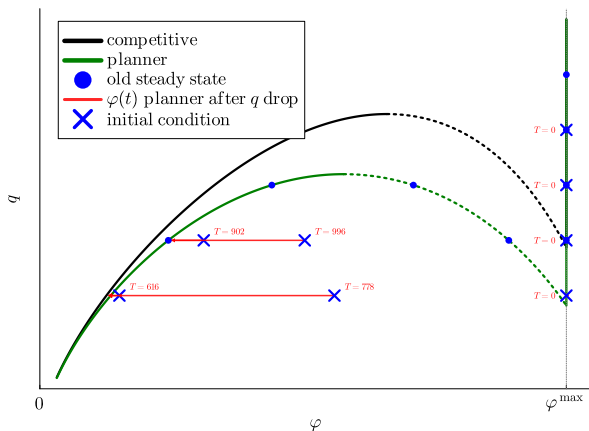
cheaper technology reduces human capital at stable interior steady states

STEADY STATES AND TRANSITION DYNAMICS



- Solid branches **stable**, dotted branch **unstable**; red paths: $\varphi(t)$ after a drop in q , with convergence time T
- Transitions between steady states are **slow**; at stable steady states, a drop in q **lowers** φ

PLANNER VS. DECENTRALIZED EQUILIBRIUM



- Planner internalizes the social value of human capital and wants to **automate less**
- Decentralized equilibrium is **efficient at the extremes**: planner and decentralized equilibrium coincide as $q \rightarrow \infty$ or $q \downarrow 0$ — inefficiency only at intermediate q

Simplified Model 2:

Endogenous Learning with Automation and Frontier Choice

- **Parameter Restrictions**

- $\psi = 1 \implies f = \min\{\bar{\tau} a_m, \bar{f}\}$ (managers not used in task production)
- Bounded frontier caps learning ($\varphi \leq \delta \bar{f} < \chi$) $\Rightarrow$ stationary equilibrium exists for every q
- Once again start with the decentralized model

- **Wage no longer depends on automation:** optimal frontier choice when $f < \bar{f}$:

$$\underbrace{\eta^{-1} \left(\frac{w_e}{1 - \eta^{-1}} \right)^{1-\eta}}_{\text{marginal profit of a new task}} = \underbrace{\frac{q}{\bar{\tau}}}_{\text{marginal cost of frontier}} \implies w_e(q) \text{ decreasing in } q$$

Cheaper technology makes the frontier cheaper to sustain $\Rightarrow$ raises the wage of workers

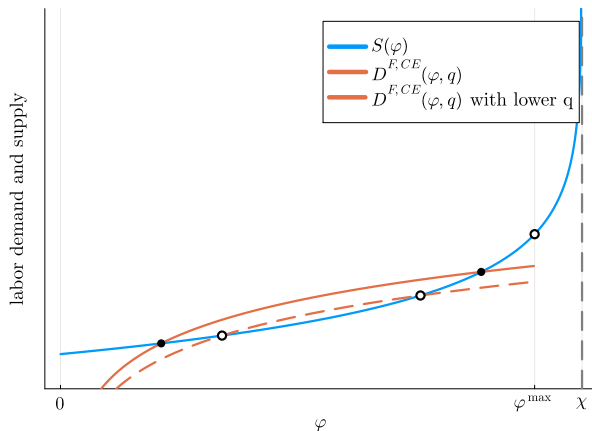
- **Steady-state labor demand** (frontier not binding):

$$D^F(\varphi, q) = \frac{\varphi}{\delta} \left(\frac{q \eta}{\bar{\tau}} \right)^{\frac{\eta}{\eta-1}} \quad \text{increasing in } q$$

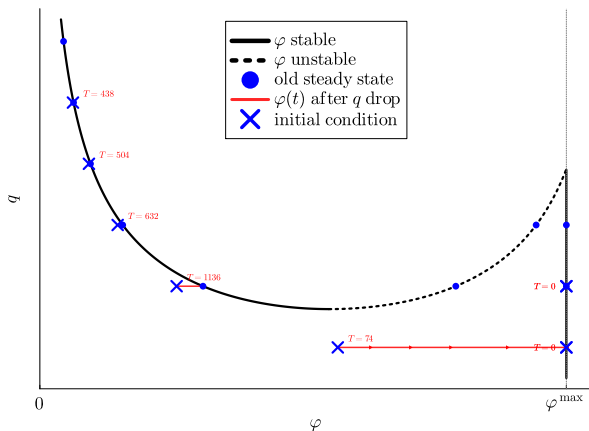
- **Same dynamics and stability as before;** only demand changes

$\implies$ Now $\partial_q \varphi < 0$:

cheaper technology raises human capital at stable interior steady states

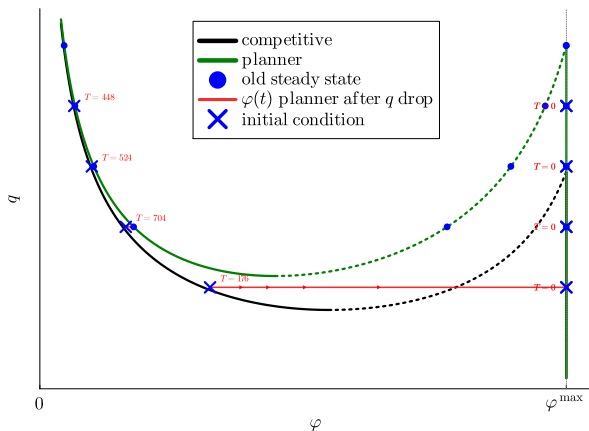


- A decline in q will cause worker wages to rise $\Rightarrow$ labor demand (in φ space) shifts down
- Interior steady states move toward each other: $\varphi_L \uparrow$ and $\varphi_H \downarrow$ — opposite of simplified model



- Along the stable branch, a drop in q now **raises** φ (sign of the comparative static flips)
- At low enough q the interior steady states disappear and the economy transitions to the **frontier corner** $\varphi^{\max}$

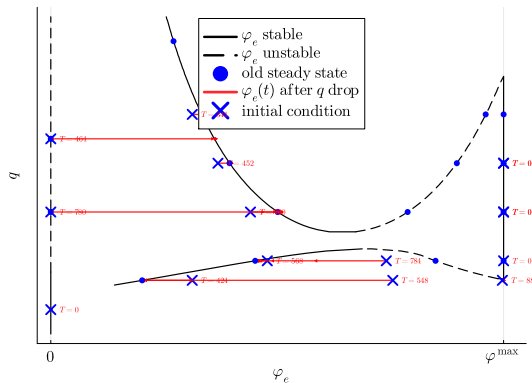
PLANNER VS. DECENTRALIZED EQUILIBRIUM



- Planner automates less and expands the frontier more $\Rightarrow$ higher φ at every q
- Planner's basin for the high-learning corner is larger: at intermediate q , the planner escapes to $\varphi^{\max}$ where the decentralized equilibrium collapses

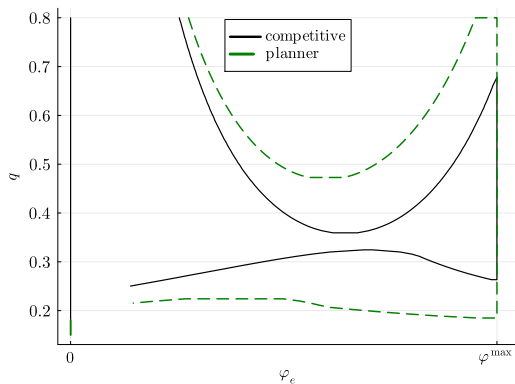
Full Model

FULL MODEL: STEADY STATES AND TRANSITION DYNAMICS



- **Frontier dominates at high q** (as ex. 2), **automation at low q** (as ex. 1); at intermediate q , interior steady states coexist with the corners
- $\varphi = 0$: **no-worker corner** (full automation); red paths: transitions after q drops, incl. **escape from the corner** at high q

FULL MODEL: PLANNER VS. DECENTRALIZED EQUILIBRIUM



- Wherever workers are retained, the planner sustains **higher learning at every price**: less automation and a larger frontier (same single wedge as in the examples)
- At low q the two coincide at the **full-automation corner**: when technology is cheap enough, even the planner shuts down worker learning

Conclusion

- Framework to explore how AI-style technology interacts with human capital accumulation
- AI effect on human capital is ambiguous:
 - AI can expand the task frontier (more learning opportunities) and can automate early rungs of the job ladder (fewer learning opportunities)
 - Unique equilibrium but multiple steady states with high and low learning
- Frontier force dominates at low technology productivity (human capital expands); automation dominates at very high productivity (human capital collapses)
- Planner wants more frontier expansion and less automation: inefficiency only at intermediate technology prices