Automation, Learning, and Career Dynamics

Hassan Afrouzi	Andres Blanco	Andres Drenik	Erik Hurst
Columbia U & Minneapolis Fed	Atlanta Fed	UT Austin	Chicago Booth

Summer 2026

Motivation Part 1: The Pessimistic View of AI

- Popular narrative that AI will eliminate many entry-level white-collar jobs

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

- Growing concern that lack of entry positions will reduce on-the-job human capital development which could eventually reduce the productivity of senior managers.
  - BCG report (2026) "*When Everyone Uses AI, Companies Risk Losing Critical Skills*"
  - The report states that 53% of surveyed business leaders cite the slower development of junior talent as a concern with evolving AI practices.

Motivation Part 2: The Optimistic View of AI

- Simultaneously, a growing belief by others that AI will lead to an increase in job creation.

"We now recognize this general purpose technology we call intelligence as an opportunity to create new industries, create brand new jobs" — Jensen Huang, CEO Nvidia 2026

- Proponents say that AI could enhance the human capital accumulation of workers by eliminating menial tasks allowing more time on activities that increase knowledge
  - McKinsey (2026) "*Reimagine learning and development for the AI age*"
  - "As AI reshapes work, winning organizations won't just automate faster – they'll learn faster"

This paper

- How does such a technology affect human capital accumulation?
- 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, countervailing 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

Model Overview

- **Time:** Continuous, indexed by $t \geq 0$
- **Agents:** a unit measure of individuals and a representative (atomistic) firm
- **Worker Heterogeneity:** Individuals differ in their 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**
- **Individual Decision:** When to become a manager (career ladder)
- **Firm Decisions:** Hire workers, hire managers, create new tasks and potentially automate existing tasks

Technology (Part 1)

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

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

  - 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:** order tasks such that $z(\tau)$ is decreasing (existence of cutoff task $\tau^*(t) \in [0, f(t)]$).

Technology (Part 2)

- **Technology for frontier:**

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

  - $\bar{f}$ bounded frontier,
  - $a_m(t)$: technology used in producing the frontier (also has exogenous price q),
  - $s(t) := \int h(x)\, dN_m(x,t)$: managerial input,
    - $h(x) = x^{\xi}$ with $\xi > 1$: human capital of managers (convex in x)
    - $dN_m(x,t)$: the number of managers
  - $\bar{\tau}$: Exogenous productivity in production of the task frontier,
  - ψ : The weight on technology in producing task frontier
  - ω : The complementarity between managers and technology in producing task frontier

- **Preferences:** $U_h(\{c\}) = \mathbb{E}\left[\int_0^\infty e^{-(\rho+\chi)t} c_{t+h,h}\, dt\right]$
- **Occupation choice:** $l(x,t) : [1,\infty) \to \{e, m\}$
  - 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 $\mathcal{A}_h := \{l(x,t)\}_{t\geq 0}$:

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

- **Human capital accumulation (learning by doing):** $\boxed{\dot{x}(t) = \varphi_l(t)\, x(t)}$ for $l \in \{e, m\}$, with
  - $\varphi_l(t) = g_l(\text{tasks done by workers}) \equiv \delta_l(f(t) - \tau^*(t))$, with $\delta_e \geq \delta_m$
  - δ_l: Governs the speed of learning; assume $\varphi^{\max} \equiv \delta_e \bar{f} < \chi$
  - τ^*: Cutoff for tasks that are automated

$\Longrightarrow$ Workers accumulate human capital based on the measure of non-automated tasks

- **Externality**: Firms do not internalize that their choice of frontier and automation affects human capital accumulation:
  - Learning is industry specific (not firm specific) + lack of commitment
- The planner's problem internalizes this effect

Firm's problem

- The 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:

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

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

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

Definition: competitive equilibrium

A competitive equilibrium consists of a household allocation $\{\mathcal{A}_h(t)\}_{t\geq 0}$, a firm allocation $\{\mathcal{A}_f(t)\}_{t\geq 0}$, prices $w_e(t)$, $w_m(t)$, and $p_a(t) = q$, and human capital growth rates $\{\varphi_l(t)\}_{l\in\{e,m\}}$ such that:

- Given prices and $\varphi_l(t)$, $\mathcal{A}_h$ and $\mathcal{A}_f$ solve the household and firm problems
- Labor markets clear for both workers and managers
- Human capital growth: $\varphi_l(t) = \delta_l \left(f(t) - \tau^*(t)\right)$ for $l \in \{e, m\}$
- The distribution of human capital evolves according to:

$$\partial_t N(x,t) = \underbrace{\chi\left(1 - N(x,t)\right)}_{\text{death}} - \underbrace{\varphi_{l(x,t)}(t)\, x\, \partial_x N(x,t)}_{\text{HC growth}}$$

Stationary equilibria: allocations, prices, and distributions are time-invariant

- **Objective:** maximize household welfare with Pareto weights $e^{-\rho h}$ across cohorts:

$$\mathcal{W}_0 = \int_{-\infty}^{\infty} e^{-\rho h}\, U_h\, dh = \frac{1}{\chi}\int_0^{\infty} e^{-\rho t}\, c_t\, dt + t.i.p. \qquad [c_t\text{: aggregate consumption}]$$

- **Problem:** choose the *entire* allocation (households, firm, technology good):

$$\max \int_0^{\infty} e^{-\rho t}\,[\,y(t) - q\,a(t)\,]\,dt$$

subject to the **same** constraints as the competitive equilibrium:

  - Production technology and feasibility in goods and labor markets
  - Human capital formation: $\varphi_l(t) = \delta_l(f(t) - \tau^*(t))$ and the law of motion of $N(x,t)$

$\Longrightarrow$ **Only difference from the market: planner internalizes that τ^* and f determine φ**

Plan of Attack: Four Steps to Understand the Economics

- Build up the model in three examples of increasing complexity before moving on to the full model:

  1. Exogenous learning + exogenous frontier
  2. Endogenous learning, exogenous frontier
  3. $+$ Endogenous frontier ($\psi = 1$: no managers in frontier production)

- Note: in the examples there are **no managers**: all individuals are workers

- Key simplification in the three examples:

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

Simplified Example 1:

Automation with *Exogenous* Learning

(No Career Choice/No Frontier Expansion)

- Example 1: Parameter Restrictions
  - Exogenous learning rate φ (with $\varphi < \chi$)
  - Exogenous frontier ($f = \bar{f}$); no career choice (everybody works)

- Human capital dynamics [learning φ, death χ, births at $x = 1$]:

$$\dot{X}(t) = \varphi X(t) - \chi \left(X(t) - 1\right)$$

  - Closed-form solution, stable since $\varphi < \chi$:

$$X(t) = \frac{\chi}{\chi - \varphi} + \left(X_0 - \frac{\chi}{\chi - \varphi}\right) e^{-(\chi - \varphi)t}$$

$\Longrightarrow$ $\boxed{\text{Human capital dynamics are independent of the price of technology } q}$

Equilibrium Automation with Exogenous Learning

- **Automation does depend on q:** **interior automation** $(0 < \tau^* < \bar{f})$ whenever labor is scarce: $X(t) < \bar{f}\left(\frac{q}{1-\eta^{-1}}\right)^{-\eta}$
  - Otherwise **no automation**: $\tau^*(t) = 0$ and $w_e(t) \leq q$ clears the market

- **With interior automation:** labor market clearing with $w_e(t) = qe^{\varepsilon\tau^*(t)}$:

$$\underbrace{(\bar{f} - \tau^*(t))\left(\frac{qe^{\varepsilon\tau^*(t)}}{1-\eta^{-1}}\right)^{-\eta}}_{\text{labor demand: declines in } \tau^*} = \underbrace{X(t)}_{\text{labor supply}}$$

- **Two properties of the benchmark:**
  - τ^* responds to q **instantly** $(T = 0)$: no transition dynamics in automation
  - **No externality**: φ fixed $\Rightarrow$ competitive equilibrium coincides with planner (efficient)

Simplified Example 2:

Automation and *Endogenous* Learning

(No Career Choice/No Frontier Expansion)

- Example 2: Parameter Restrictions
  - Endogenous learning rate: $\varphi(t) = \delta\left(\bar{f} - \tau^*(t)\right)$
  - Exogenous frontier ($f = \bar{f}$); no career choice (everybody works)

Steady States in Terms of the Learning Rate (example 2)

- **Human capital dynamics as in example 1**, but $\varphi(t)$ is now an equilibrium object:

$$\dot{X}(t) = \varphi(t)X(t) - \chi\left(X(t) - 1\right) \quad \Longrightarrow \quad X_{ss} = \frac{\chi}{\chi - \varphi}$$

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

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

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

Steady States in Terms of the Learning Rate (example 2)

- **Human capital dynamics as in example 1**, but $\varphi(t)$ is now an equilibrium object:

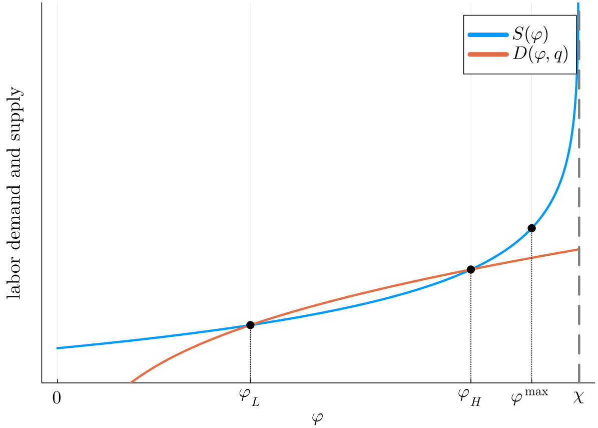
$$\dot{X}(t) = \varphi(t)X(t) - \chi\left(X(t) - 1\right) \quad \Longrightarrow \quad X_{ss} = \frac{\chi}{\chi - \varphi}$$

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

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

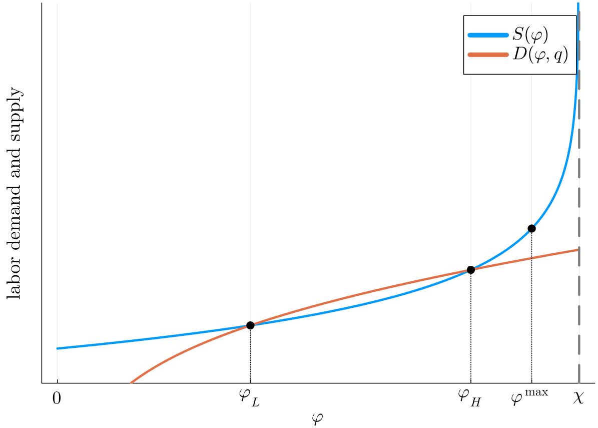
  No-automation corner: $\varphi = \delta\bar{f}$ is a steady state whenever $D(\delta\bar{f}, q) \leq S(\delta\bar{f})$

- **Both labor demand and labor supply increase with human capital accumulation:**
  - $\varphi = 0$: $D(\varphi, q) = 0$ and $S(\varphi) > 0$
  - $\varphi \to \chi$: $D(\varphi, q)$ is finite and $S(\varphi) \to \infty$



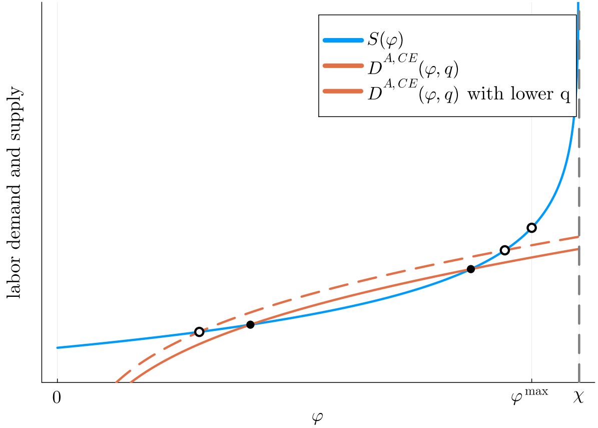
- **Two interior steady states:** $D(\varphi_L, q) = S(\varphi_L)$ (low-learning) and $D(\varphi_H, q) = S(\varphi_H)$ (high-learning)
- **Third steady state** at the bounded frontier ($\varphi^{\max} = \delta\bar{f}$)

Economics of multiplicity (example 2): labor demand and labor supply



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

ECONOMICS OF MULTIPLICITY (EXAMPLE 2): A DECLINE IN q



- 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 $\varphi_H \uparrow$

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

$$D\left(\varphi(t), q\right) = X(t) \quad \Longrightarrow \quad \varphi(t) = \varphi\left(X(t), q\right), \text{ increasing in } X(t) \text{ and } q$$

- **Dynamics of the state:** $\dot{X}(t) = F(X(t), q) \equiv \varphi(X(t), q)X(t) - \chi\left(X(t) - 1\right)$

- **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:**

$$X'_{ss}(q) = \frac{\partial_q \varphi\left(X_{ss}, q\right) X_{ss}}{-F_1(X_{ss}, q)} \quad \Longrightarrow \quad \text{sign}\left[X'_{ss}(q)\right] = \text{sign}\left[\partial_q \varphi\right]$$

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

cheaper technology reduces human capital at stable interior steady states

From Human Capital Dynamics to Learning-Rate Dynamics

- Since $\varphi(X, q)$ is **increasing in X**, the dynamics of $\varphi(t)$ mirror those of $X(t)$:

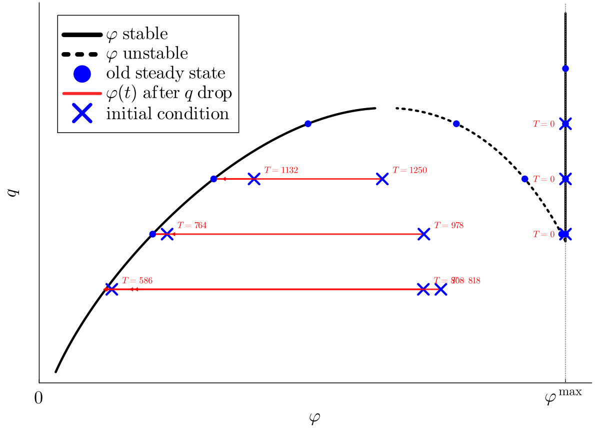
$$\dot{\varphi}(t) = \frac{\chi - \varphi(t)}{\underbrace{\partial_\varphi D\left(\varphi(t), q\right)}_{>0}} \underbrace{\left[S\left(\varphi(t)\right) - D\left(\varphi(t), q\right)\right]}_{\text{steady-state excess supply of labor}}$$

- **Intuition:** the market clears through quantities:

  excess supply $\Rightarrow$ wage falls $\Rightarrow$ automation recedes $\Rightarrow$ worker tasks widen $\Rightarrow$ φ rises

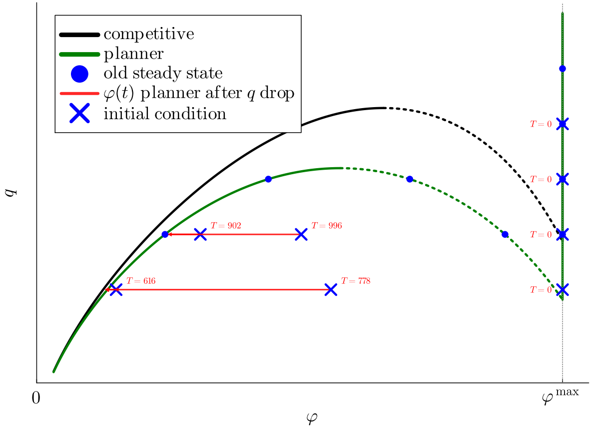
- **Stability in the figure:** a crossing is stable iff excess supply is positive below it and negative above it (D steeper than S)

$\Longrightarrow$ **φ_L and $\varphi^{\max}$ are stable; φ_H is unstable** and separates their basins



- 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. competitive equilibrium (example 2)



- Planner **automates less**: steady states compressed toward the interior
- CE is **efficient at the extremes**: planner and CE coincide as $q \to \infty$ or $q \downarrow 0$ — inefficiency only at intermediate q

Simplified Example 3:

Endogenous Learning with Automation and Frontier Choice

- Example 3: 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

- **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 ⇒ raises the demand for — and the wage of — workers

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

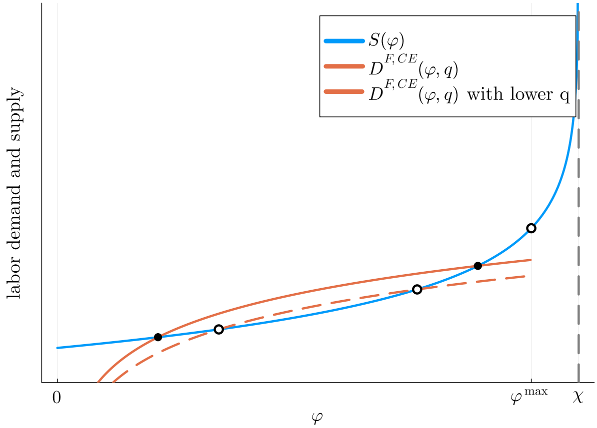
$$D^F(\varphi, q) = \frac{\varphi}{\delta}\left(\frac{q\,\eta}{\bar{\tau}}\right)^{\frac{\eta}{\eta-1}} \qquad \text{increasing in } q$$

- **Same dynamics and stability as example 2** — only demand changes

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

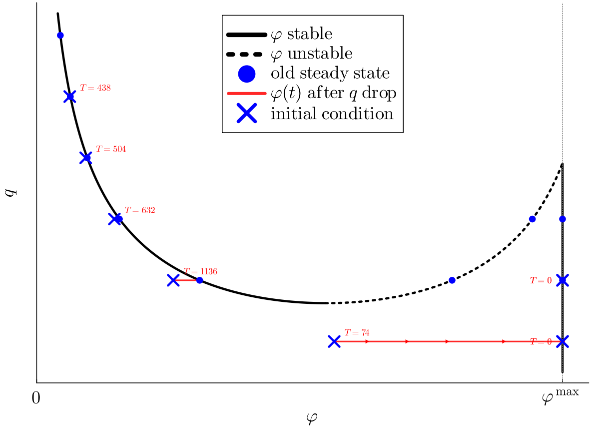
$\boxed{\text{cheaper technology raises human capital at stable interior steady states}}$

Economics of multiplicity (example 3): a decline in q



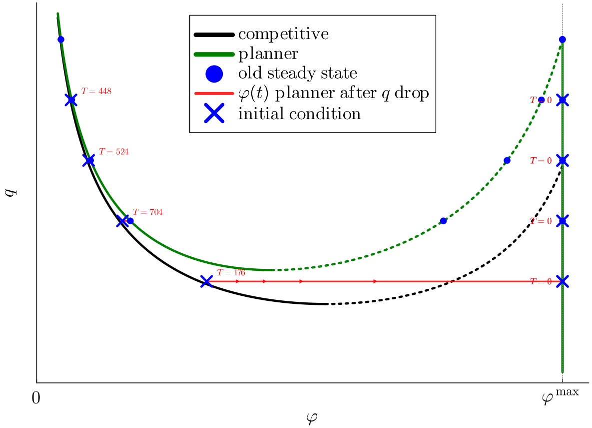
- **A decline in q** will cause worker wages to rise $\Rightarrow$ **labor demand (in φ space) shifts down**
- Interior steady states **move toward each other**: $\varphi_L \uparrow$ and $\varphi_H \downarrow$ — opposite of example 2

Steady states and transition dynamics (example 3)



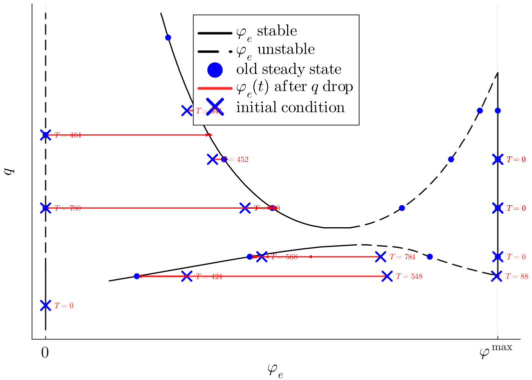
- Along the stable branch, a drop in q now **raises** φ — the sign of the comparative static flips
- At low enough q the interior steady states disappear and the economy transitions to the **frontier corner** $\varphi^{\max}$

Planner vs. competitive equilibrium (example 3)



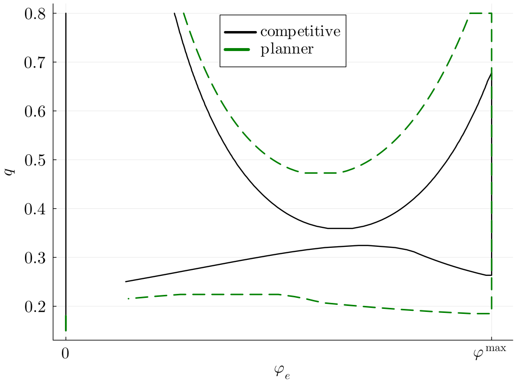
- Planner **automates less and expands the frontier more** $\Rightarrow$ higher φ at every q
- Planner's basin for the high-learning corner is **much larger**: at intermediate q, the planner escapes to $\varphi^{\max}$ where the CE collapses

Full Model



- **Frontier dominates at high q** (as ex. 3), **automation at low q** (as ex. 2); 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. Competitive 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

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