Scenarios for the Transition to AGI

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Motivation

- AI is advancing rapidly, and the pace has been accelerating
- Recent progress has brought the potential for Artificial General Intelligence (AGI) within tangible reach:
  - Def: AGI is the ability of machines to perform all work tasks that humans can do
- AGI promises significant productivity gains while substituting labor

Questions

- What would the transition to AGI look like?
- What would AGI imply for output and wages?
- Under what conditions would wages collapse?

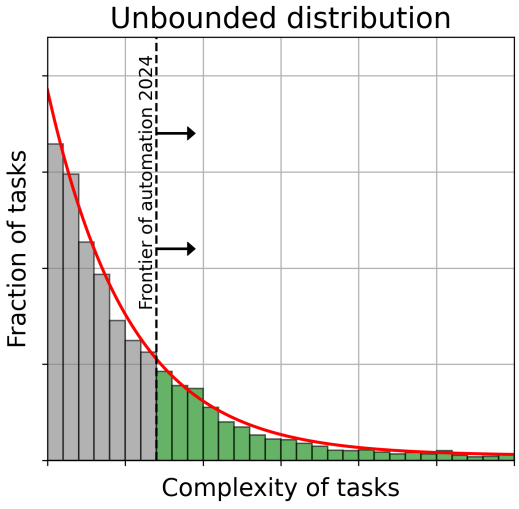
Key Assumptions

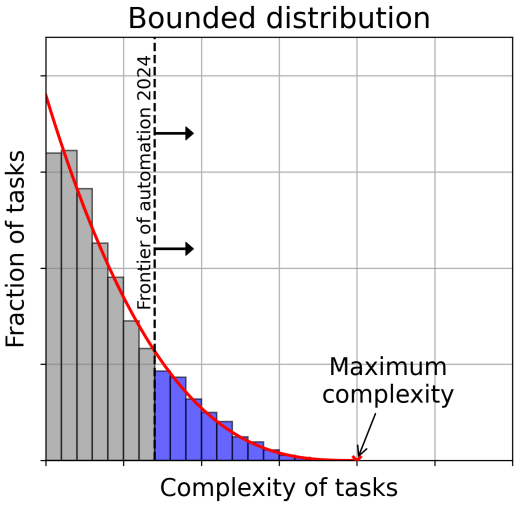
- Work is made up of elementary tasks (far smaller than O*Net tasks)
- Main distinguishing characteristic of tasks: complexity, which depends to an important extent on their "compute intensity"

- Consider different scenarios for the distribution of tasks in complexity space ("tasks in compute space"):
  - Unbounded distributions (e.g., Pareto): some human tasks will always remain too complex for machines
  - Bounded distributions (e.g., beta): there is a maximum complexity level for human tasks

- Alternative interpretation for "complexity:" we reserve certain tasks for humans

Scenarios for Task Complexity





Key Results

- Output impact depends on
  1. productivity gains from automation
  2. capital accumulation
- Wage impact additionally depends on:
  3. labor displacement from automation

$\Rightarrow$ **race between automation and capital accumulation**
(instead of Tinbergen's "race between education and technology")

- Wages collapse
  - if automation outpaces capital accumulation
  - OR shortly before full automation is reached

A Model of Automation

Static Environment (a la Zeira, 1998; Acemoglu-Restrepo, 2018)

- There is a representative household endowed with $L = 1$ units of labor and $K > 0$ units of capital.
- There is a continuum of tasks differing in computational complexity ($i \geq 1$) with an associated CDF $\Phi(i)$.
- Aggregate output Y is

$$Y = A\left[\int_i y(i)^{\frac{\sigma-1}{\sigma}} d\Phi(i)\right]^{\frac{\sigma}{\sigma-1}}$$

  where $y(i)$ is the amount of type i tasks.
- Each task is performed according to a production function

$$y(i) = \begin{cases} k(i) + \ell(i) & \text{for } i < I \\ \ell(i) & \text{for } i \geq I \end{cases}$$

  where I is an automation index.

A Model of Automation

Strategies:

- The representative household supplies her labor and capital at the prevailing factor prices w and R.
- The representative firm maximizes profits by hiring capital $k(i)$ and labor $\ell(i)$ for each task i to produce $y(i)$.
- The firm's maximization problem is:

$$\max_{k(i),\ell(i)} Y - R\int_i k(i)d\Phi(i) - w\int_i \ell(i)d\Phi(i)$$

A Model of Automation

Equilibrium:

- An equilibrium consists of $\{k(i), \ell(i), y(i)\}_{i \geq 0}$ and factor prices w and R such that the firm solves its maximization problem and markets for capital and labor clear.

$$\int_i k(i) d\Phi(i) = K \qquad \int_i \ell(i) d\Phi(i) = 1$$

- There are no market imperfections making this equilibrium the first-best of the economy.

Scarcity of Labor

Threshold

Lemma 1 (Scarcity of Labor): The capital intensity K/L of the economy defines a threshold $\hat{I}$ given by

$$\Phi\left(\hat{I}\right) = \frac{K/L}{1 + K/L},$$

such that there are two regions:

Region 1 (Abundant K, Scarce L) for $I < \hat{I}$

- Wages $w > R$ returns on capital
- Labor used only for unautomated tasks, production is CES

Region 2 (Equally Scarce K and L): for $I \geq \hat{I}$

- Wages $w = R$ returns on capital
- Labor and capital effective substitutes
- Production is linear: $Y = A(K + L)$

Scarcity of Labor

Allocation of K and L: $k = K/\Phi(I)$, $\ell = L/(1-\Phi(I))$

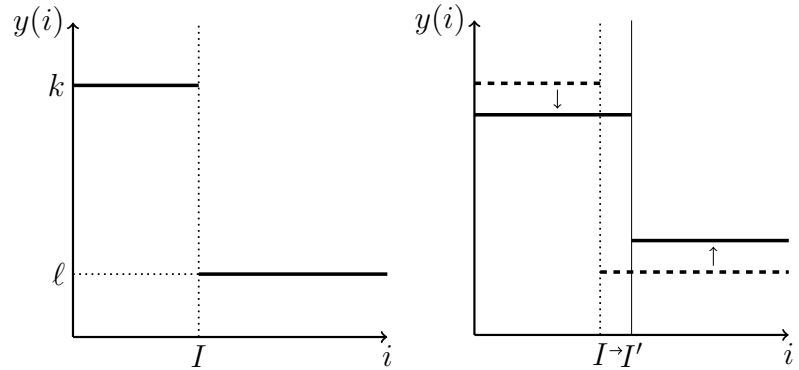
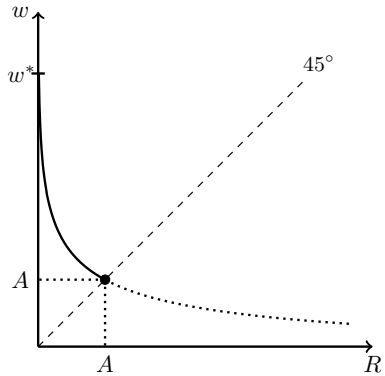


Figure: Automation relieves the scarcity of labor ($k/\ell \downarrow$)

Factor Price Frontier

The factor price frontier is the dual of isoquants and depicts all possible combinations of competitive factor prices R and w that may result from different ratios of K/L under profit maximization.



Factor Price Frontier

- When $I < \hat{I}$, the FPF is given by all pairs of (w, R) that satisfy unit cost $UC(w, R) = 1$.
- As $K/L \to \infty$, R goes to zero, whereas w converges to $w^*(I) = A(1 - \Phi(I))^{\frac{1}{\sigma - 1}}$.
- Conversely, when $I \geq \hat{I}$, the factor price frontier is degenerate and consists of a single point $w = R = A$.

Factor Price Frontier

- Increases in A move the FPF outwards

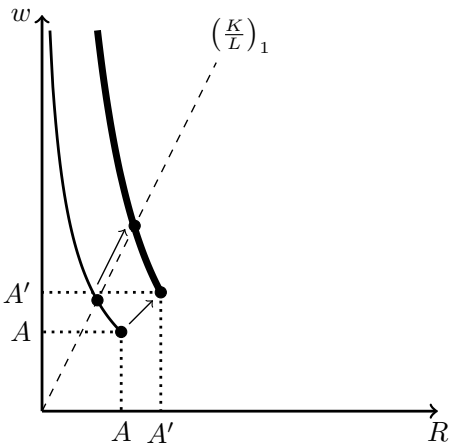
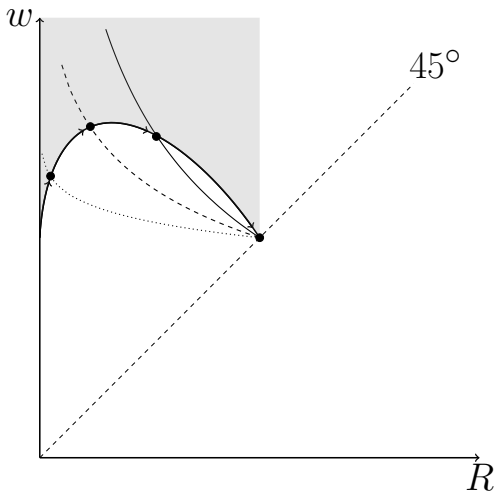


Figure: Rising A

The Path of Automation in the Space of Factor Prices

- Increasing automation first raises and then depresses wages
- Returns to capital increase strictly monotonically



Effects of Automation

Lemma (Automation and Output)

An increase in automation I raises output as long as $I < \hat{I}$, and leaves output unaffected otherwise.

Lemma (Automation and Wages)

An increase in automation I always raises R and raises w for sufficiently low I (sufficiently high K/L), but lowers w for sufficiently high I (sufficiently low K/L). In the limit cases of $\Phi(I) = 0$ and $\Phi(I) \geq \kappa/(1+\kappa)$, wages equal $w = A$. The latter condition holds for any K/L if $\Phi(I) = 1$.

Dynamics

The Race between Automation and Capital Accumulation

- We assume exponential growth in the maximum automatable task complexity (automation index I)
  $\Longrightarrow$ reflects Moore's law & its cousins
- Dynamics of output and wages depend on the interplay between
  - task automation $d\Phi(i)$ – which depends on the scenario $\Phi(I)$
  - capital accumulation

Consumer Problem

The representative household solves:

$$\max_{\{C_t\}} U = \int_0^{\infty} e^{-\rho t} u(C_t) dt$$

subject to the law of motion for capital:

$$\dot{K}_t = F(K_t, L_t; I_t) - \delta K_t - C_t$$

for given K_0.

Bounds for Output and Wages

Proposition

For any distribution $\Phi(i)$ of tasks in compute space and exogenous growth in the automation index I_t, the paths of capital, output, and wages lie between lower and upper bounds:

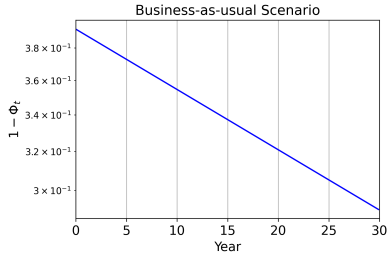
$$
\begin{aligned}
K^- \leq & K_t \leq K_t^+ \\
Y_t^- \leq & Y_t \leq Y_t^+ \\
w_t^- \leq & w_t \leq w_t^+
\end{aligned}
$$

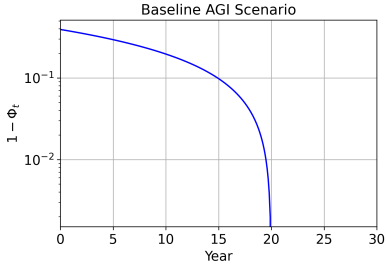
- *lower bounds: defined by the fixed-capital case with $K_t = K^- = K_0 \ \forall t$*
- *upper bounds: defined by instantenously optimal capital accumulation s.t. $F_K\left(K_t^+, L, I_t\right) = R = \rho + \delta \ \forall t$*

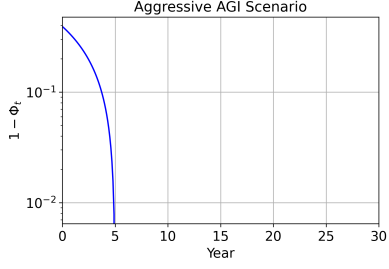
Dynamics of the Bounds

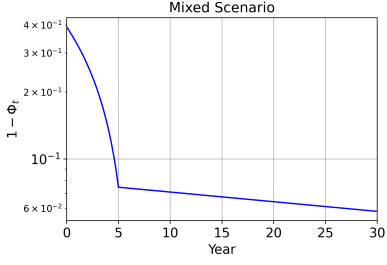
- The lower bound w_t^- first rises and then declines in I_t.
- w_t^- declines to A in finite time if full automation is reached asymptotically, i.e. $\lim_{I \to \infty} \Phi(I) = 1$.
- All three upper bounds are increasing in I_t.
- If the economy reaches full automation, $\Phi(I_t) = 1$, then the upper bounds are $K_t^+ = \infty$ and $Y_t^+ = \infty$, and the upper bound on wages discontinuously collapses to $w_t^+ = A$.

Four Scenarios (Log of Mass of Unautomated Tasks)









Race Between Automation and Capital Accumulation

- What determines the dynamics of wages?
- Analyze the threshold where wage effects of automation and capital accumulation offset each other
- Examine $dw_t = dF_L = 0$:

$$s_t Y_t \cdot F_{KL} = -F_{L\Phi}\dot{\Phi}_t$$

- The "balancing" savings rate, given Φ and g, offsets the effect of automation on wages:

$$\tilde{s}_t = \left[\left(\kappa + \frac{1}{1-\sigma}\right) - \frac{\sigma}{1-\sigma}(k/\ell)^{\frac{1-\sigma}{\sigma}}\right] \cdot \frac{K_t}{Y_t} \cdot \frac{\phi_t I_t}{\Phi_t} \cdot g$$

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$$\tilde{s}_t = \Bigg[\underbrace{\left(\kappa + \frac{1}{1-\sigma}\right)}_{\text{Displacement effect}} - \underbrace{\frac{\sigma}{1-\sigma}(k/\ell)^{\frac{1-\sigma}{\sigma}}}_{\text{Productivity effect}} \Bigg] \cdot \frac{K_t}{Y_t} \cdot \frac{\phi_t I_t}{\Phi_t} \cdot g$$

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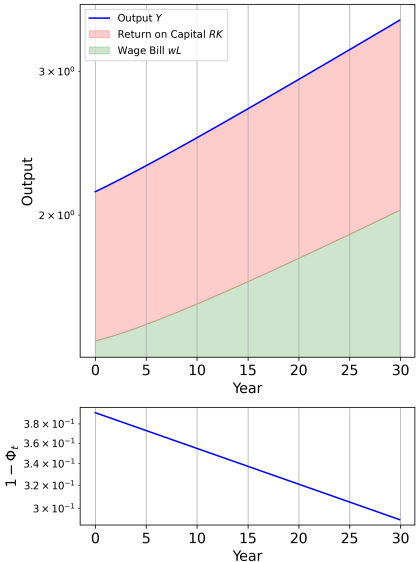
Path of Wages Under the Business-as-usual Scenario



Business-as-usual Scenario: Long-run Dynamics of Wages

Proposition

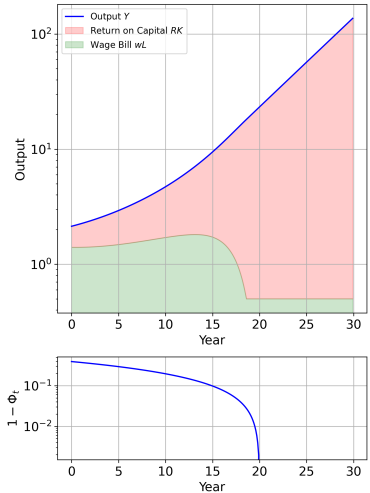
Suppose the complexity distribution of tasks is Pareto and that the economy starts in region 1, i.e., $I_0 < \hat{I}_0$. Then the growth of wages and long-run labor shares are characterized by two thresholds on the rate of automation λg:

1. If $\lambda g \leq \frac{A-\rho-\delta}{\eta} \cdot (1-\sigma)$ then wages grow exponentially at an asymptotic rate $\frac{\lambda g}{1-\sigma}$ and the labor share converges to a constant strictly larger than zero.
2. If $\frac{A-\rho-\delta}{\eta} \cdot (1-\sigma) \leq \lambda g \leq \frac{A-\rho-\delta}{\eta}$ then wages grow exponentially at an asymptotic rate $\frac{1}{\sigma}\left(\frac{A-\rho-\delta}{\eta} - \lambda g\right)$ and the labor share converges to zero.
3. Lastly, $\lambda g > \frac{A-\rho-\delta}{\eta}$ then $w_t = A$ for sufficiently large t and the labor share converges to zero.

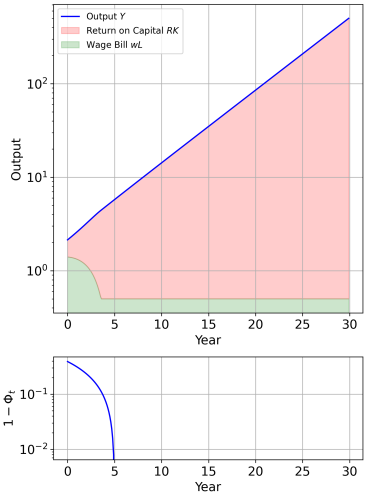
Paths of Wages under AGI

- Business-as-usual scenario may result in sustained wage growth
- But AGI scenarios end with a collapse in wages
- Depending on the upper bound on task complexity, the collapse may happen sooner

Paths of Wages Under the AGI Scenarios

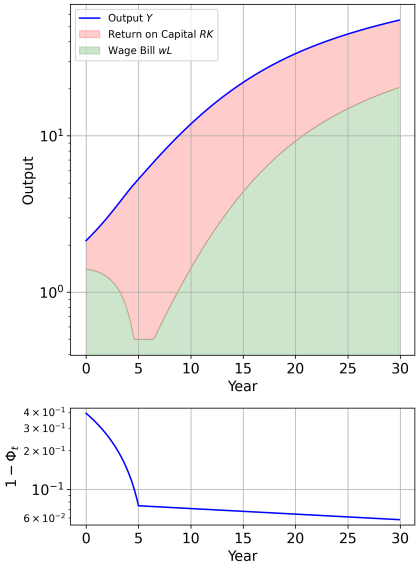


Baseline AGI scenario

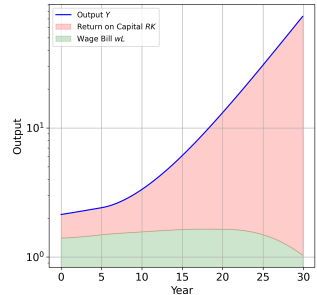


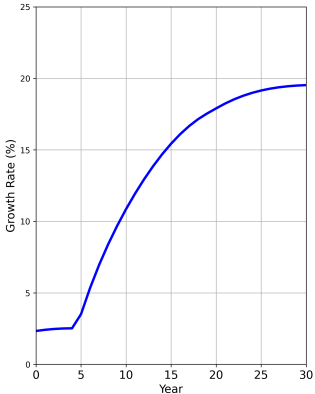
Aggressive AGI scenario

Path of Wages Under the Mixed Scenario



Slow Diffusion





Extensions

1. Fixed factors and the return of scarcity
2. Automating technological progress (TFP)
3. Nostalgic jobs performed by humans
4. Heterogenous skills
5. Software AGI vs hardware and specific capital

Extension 1: Fixed Factors and the Return of Scarcity

- Lumping all factors other than labor together into "capital" is simplification - particularly relevant during Industrial Age when labor earned majority income
- Once labor is no longer most important factor, it is useful to disentangle capital
- Distinguish between non-labor factors in fixed supply and reproducible factors
  - Fixed supply factors: matter, land, space, minearals, solar radiation
  - Reproducible factors: factories, robots, power plants, tools
- Both types of factors are sources of scarcity
- Difficult to predict which scarce factors will matter the most in an AGI-powered future
  - microchips, semiconductor fabrication equipment ("fabs"), matter or energy,...

Incorporating Fixed Factors into Analysis

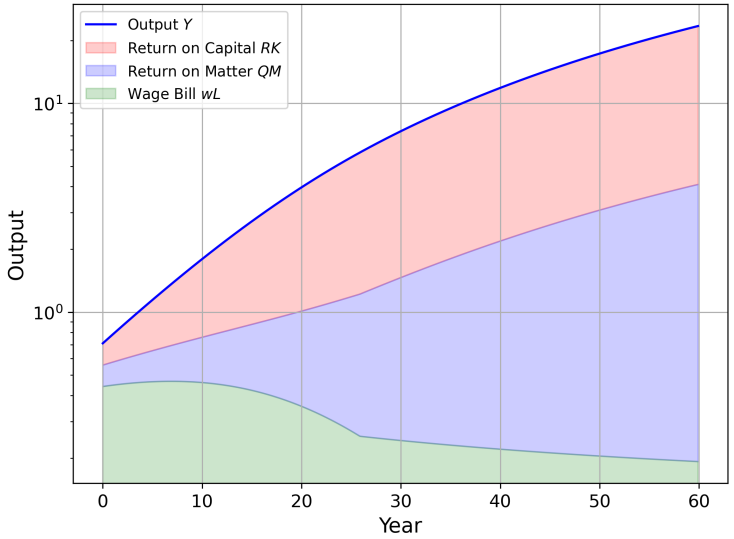
- Introduce a fixed factor ("matter") denoted by M
- The aggregate production function is a Cobb-Douglas aggregator of the task composite and matter

$$Y = A\left[\int_i y(i)^{\frac{\sigma-1}{\sigma}} d\Phi(i)\right]^{\frac{\sigma}{\sigma-1}\cdot\alpha} M^{1-\alpha}$$

  where $1-\alpha \in (0,1)$ is the income share of matter
- For a given M, results on the scarcity of labor and the two ensuing regions holds
- However, the aggregate production function in region 2 exhibits decreasing returns in $K+L$

$$Y = A(K+L)^{\alpha} M^{1-\alpha}$$

Path of Wages with Matter



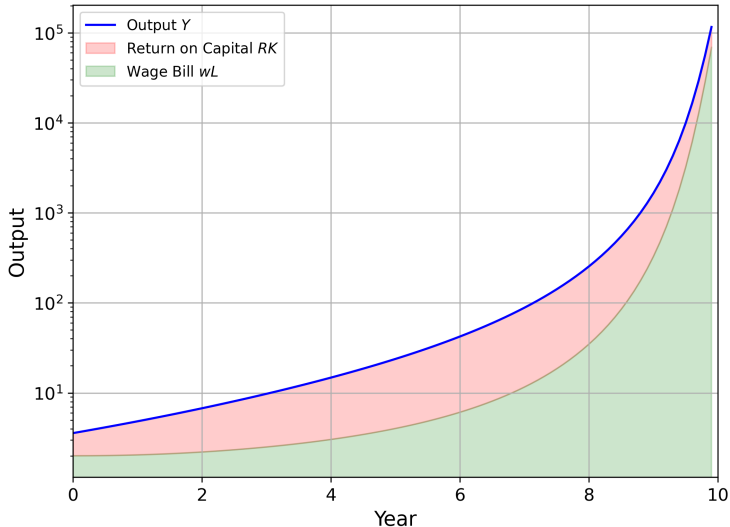
Extension 2: Automating Technological Progress

- Production of new ideas: $\log \dot{A}_t = \log A_t^{\theta} + \int \log x_t(i) d\Gamma(i)$
  - θ governs the knowledge spillover
- Atomistic tasks for knowledge production

$$x(i) = \begin{cases} k_A(i) + \ell_A(i) & \text{for } i < I \\ \ell_A(i) & \text{for } i \geq I \end{cases}$$

- once goods production OR knowledge production have been sufficiently automated, the economy experiences ever-increasing growth rates

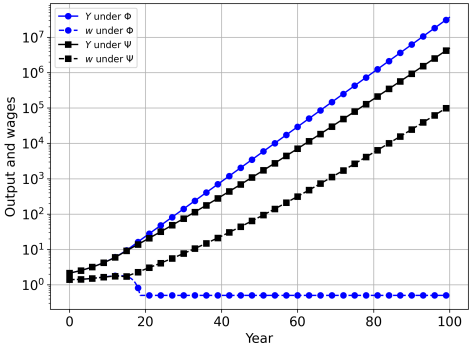
Path of Wages under Automated Technological Progress

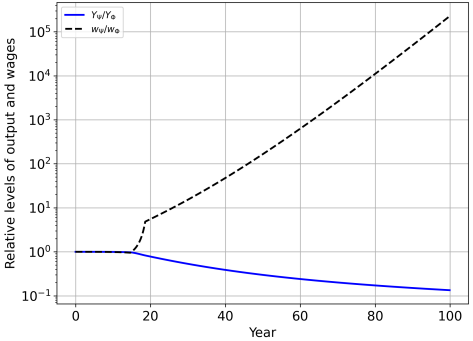


Extension 3: Nostalgic Jobs and Holding Back Automation

- Society may preserve certain tasks for humans
- Define a separate distribution function $\Psi(I)$
  - Fraction of tasks that are actually automated given I
  - $\Phi(I)$ captures the technological possibility of automation
- $\Psi(I) \leq \Phi(I)$: feasibility constraint of automation

Relative Output and Wages under Limited Automation





Extension 4: Heterogeneous Worker Skills

- Automation hits different workers at different times
- Assume continuous and uni-dimensional skill, captured by parameter J
- A fraction $\Upsilon(J)$ of workers are perfectly substitutable by machines and earn

$$w_j = A, \ \ \forall j < J$$

- Skilled workers of mass $1 - \Upsilon(J)$ earn

$$w_j = F_L(K + \Upsilon(J), 1 - \Upsilon(J)), \ \ \forall j > J$$

$\rightarrow$ ever smaller fraction of workers earning ever greater returns

Extension 5: Compute as Specific Capital

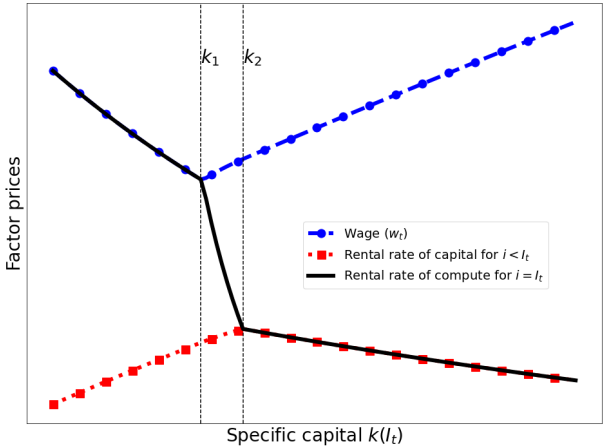
- Many types of capital are specific to the task for which they were created
  - most relevant current example: AI requires cutting-edge compute
  - Scarcity of compute may slow down the ongoing AI take-off
- Reallocation is difficult or even impossible
- Extend our framework by assuming that each unit of capital investment is specific to a task i and can only be invested once the task is automated

$\rightarrow$ in short run, specific capital (compute) is scarce and as valuable as labor because the two are perfect substitutes

$\rightarrow$ over time capital accumulation dissipates scarcity rents

$\rightarrow$ in the long run, all types of capital are "equal"
(and with sufficient automation, labor too)

Factor Prices and Compute



Conclusions

- Rapid automation may fundamentally change the structure of our economy
- Biggest concern: fate of labor
  - Race between automation and capital accumulation
  - Under AGI, labor will lose the race
  - But this may happen even pre-AGI
- Growth take-off under AGI makes it feasible to compensate workers so everyone is better off
  - Will we succeed in doing so?