# Competing Teams

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# Introduction

- Firms often compete in output markets that are not competitive
  - Patent race between pharmaceuticals (winner-takes-all)
  - Positive knowledge spillovers from copying technology
  - Market Power and oligopoly
  - ...
- Externalities affect effort provision (tournaments, contests,...)
- But also: how firms choose skill composition
  - Pharmaceutical with best scientists is more likely to get patent
  - Firms spend time and resources picking best team (including poaching from competitors)
  - ...

# The Problem

- We analyze assortative matching with externalities
  - Standard model: match output depends only on matched pair
  - Here: match output depends also on other pairs
- Natural extension of Becker (1973)
  1. The output market is non-competitive
  2. The input/labor market is competitive
- Issues of interest:
  - Optimal versus equilibrium matching
  - Given output market: welfare improving intervention in input market
- Applications
  1. Knowledge Spillovers and within/between firm inequality
  2. Oligopoly
  3. Policy and Sports Competitions

# Take Away

1. Multiple equilibria
2. Interior equilibrium and planner's solution: mixed matching
3. Complementarity is not sufficient for PAM
4. Inefficiency: equilibrium vs. planner's allocation discontinuous
5. Applications: rationale evolution within- and between-firm inequality

# The Setup

## Overview of the model

- Large number of heterogeneous workers (and firms)
- Two stages:
  1. Matching: Workers form teams of size 2 (competitive labor market)
  2. Competition: Teams compete in output market (incomplete markets)
- Second stage: match payoff depends on composition of competitor(s)
  1. Aggregate Spillovers: endogenous growth (copying)
  2. Pairwise Assignment with Local Spillovers
     - A Random Pairwise Assignment: sports competitions
     - B Deterministic Pairwise Assignment: oligopoly
     - C Directed Pairwise Assignment: internalize externality
- First stage: Analysis of sorting patterns
  - Planner vs. Competitive Equilibrium
  - Wedge between two outcomes due to externalities

# The Setup

- Continuum of agents
  1. Binary Types
     - Each has a 'type' $x \in \{\underline{x}, \overline{x}\}$, $\overline{x} > \underline{x}$ (equal measure)
     - Workers form teams of size 2
       $\overline{X} = \{\overline{x}, \overline{x}\}$ or $\underline{X} = \{\underline{x}, \underline{x}\}$ or $\hat{X} = \{\overline{x}, \underline{x}\}$ with $\underline{X} < \hat{X} < \overline{X}$
  2. Continuum of types $x$
- Transferable utility
- Matching $\mu$ partitions population in pairs:
  - PAM $\mu_+$ binary: half of the teams are $\overline{X}$ and half $\underline{X}$
  - NAM $\mu_-$ binary: all the teams are $\hat{X}$
  - Mixed $\mu(\alpha)$: fraction $\frac{\alpha}{2}$ are $\overline{X}, \underline{X}$; fraction $1 - \alpha$ are $\hat{X}$

# The Setup

- Aggregate externality: $\mathcal{V}(X|\mu)$
- Pairwise assignment: Teams compete pairwise in downstream interaction (e.g., output market) against a randomly drawn team
  - $V(X_i|X_j)$: match output of team $X_i$ when competing with $X_j$
  - With Random Assignment

$$\mathcal{V}(X_i|\mu_+) = \mathbb{E}_{\mu_+}[V(X_i|\tilde{X}_j)] = \frac{1}{2}V(X_i|\overline{X}) + \frac{1}{2}V(X_i|\underline{X})$$
$$\mathcal{V}(X_i|\mu_-) = \mathbb{E}_{\mu_-}[V(X_i|\tilde{X}_j)] = V(X_i|\hat{X})$$

- Gradually, provide micro foundations for $\mathcal{V}(X|\mu) \rightarrow V(X_i|X_j) \rightarrow ...$

# The Setup

## An example – Patent Race

- Research: uncertainty about the exact outcome $v_i$
  1. Form R&D teams
  2. Draw uncertain research output $v_i$:
     - $v_i \in \{0, v\}$
     - probability of $v$ given team $X_i$: $p_i = p(X_i)$ (with $\overline{p} > \hat{p} > \underline{p}$)
  3. Winner takes all: $\max\{v_i, v_j\}$ (half in case of a tie)
- Expected payoff:

$$V(X_i|X_j) = p_i p_j \frac{v}{2} + p_i(1 - p_j)v = vp_i - \frac{v}{2} p_i p_j$$

$$\Rightarrow \quad \text{e.g. } V(\overline{X}|\underline{X}) = v\overline{p} - \frac{v}{2}\overline{p}\underline{p} \quad \text{and} \quad V(\overline{X}|\overline{X}) = v\overline{p} - \frac{v}{2}\overline{p}\overline{p}$$

$$\Rightarrow \quad \mathcal{V}(\overline{X}|\mu_+) = \frac{1}{2}\left(v\overline{p} - \frac{v}{2}\overline{p}\underline{p}\right) + \frac{1}{2}\left(v\overline{p} - \frac{v}{2}\overline{p}^2\right)$$

# Solution

**Planner:** Takes as given output market competition and chooses $\mu$ that maximizes sum of teams' outputs

- PAM optimal if

$$\mathcal{V}(\overline{X}|\mu_+) + \mathcal{V}(\underline{X}|\mu_+) \geq 2\mathcal{V}(\hat{X}|\mu_-)$$

- NAM optimal if

$$\mathcal{V}(\overline{X}|\mu_+) + \mathcal{V}(\underline{X}|\mu_+) \leq 2\mathcal{V}(\hat{X}|\mu_-)$$

- Reduces to supermodularity (or submodularity) without externalities

$$\mathcal{V}(\overline{X}) + \mathcal{V}(\underline{X}) \quad \text{vs.} \quad 2\mathcal{V}(\hat{X})$$

# Solution

**Competitive Equilibrium:** Agents take market wages and matching as given when they choose partners

- $(\underline{w}, \overline{w}, \mu)$ such that $(i)$ each type maximizes his payoff given wages; and $(ii)$ choices are consistent with $\mu$ (market clearing)
- PAM if

$$\begin{aligned} \mathcal{V}(\overline{X}|\mu_+) - \overline{w} &\geq \mathcal{V}(\hat{X}|\mu_+) - \underline{w} \\ \mathcal{V}(\underline{X}|\mu_+) - \underline{w} &\geq \mathcal{V}(\hat{X}|\mu_+) - \overline{w} \end{aligned}$$

$\Rightarrow \mathcal{V}(\cdot|\mu_+)$ supermodular, or

$$\mathcal{V}(\overline{X}|\mu_+) + \mathcal{V}(\underline{X}|\mu_+) \geq 2\mathcal{V}(\hat{X}|\mu_+)$$

- Wages: $\overline{w} = \frac{1}{2}\mathcal{V}(\overline{X}|\mu_+)$ and $\underline{w} = \frac{1}{2}\mathcal{V}(\underline{X}|\mu_+)$

# Results

- Let $\frac{\alpha}{2}$ be fraction of $\overline{X}$, $\underline{X}$ teams, and $(1-\alpha)$ fraction of $\hat{X}$ teams
- Define
$$\Gamma(\alpha) = \mathcal{V}(\overline{X}|\alpha) + \mathcal{V}(\underline{X}|\alpha) - 2\mathcal{V}(\hat{X}|\alpha),$$
This function is linear in $\alpha$, so is $\mathcal{V}(X|\alpha)$
$$\mathcal{V}(X|\alpha) = \alpha\mathcal{V}(X|1) + (1-\alpha)\mathcal{V}(X|0)$$
This implies
$$\Gamma(\alpha) = \alpha\Gamma(1) + (1-\alpha)\Gamma(0)$$

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$$\mathcal{V}(X|\alpha) = \alpha\mathcal{V}(X|1) + (1-\alpha)\mathcal{V}(X|0)$$

This implies

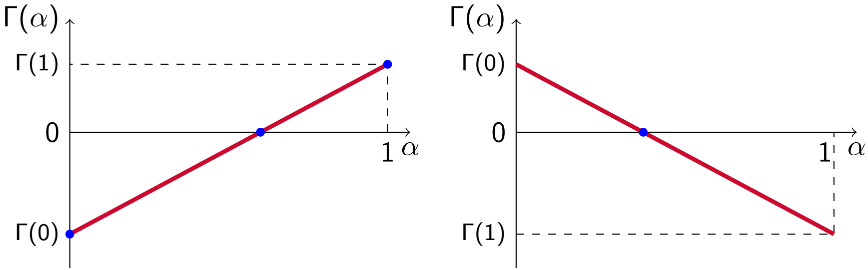
$$\Gamma(\alpha) = \alpha\Gamma(1) + (1-\alpha)\Gamma(0)$$

## Proposition

*A competitive equilibrium exists. It exhibits PAM if* $\Gamma(1) \geq 0$*, NAM if* $\Gamma(0) \leq 0$*, and it is interior with* $0 < \alpha < 1$ *if* $\Gamma(\alpha) = 0$*.*

# Results

- Unlike Becker, without externalities
  1. There can be interior equilibria $\alpha \in (0, 1)$
  2. There can be multiple equilibria



# Results – Planner

- Planner's solution can be interior:

$$\max_{\alpha\in[0,1]} \quad \frac{1}{2}\left(\frac{\alpha}{2}\mathcal{V}(\overline{X}|\alpha)+\frac{\alpha}{2}\mathcal{V}(\underline{X}|\alpha)+(1-\alpha)\mathcal{V}(\hat{X}|\alpha)\right)$$

  or equivalently

$$\max_{\alpha\in[0,1]} \frac{1}{2}\left(\frac{\alpha^2}{2}A+\frac{\alpha}{2}B+C\right)$$

  where $A\equiv\Gamma(1)-\Gamma(0)$, $B\equiv\Gamma(0)+2(\mathcal{V}(\hat{X}|1)-\mathcal{V}(\hat{X}|0))$, $C\equiv\mathcal{V}(\hat{X}|0)$
- Quadratic objective: convex $\Rightarrow$ corner; concave $\Rightarrow$ interior or corner

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- Quadratic objective: convex $\Rightarrow$ corner; concave $\Rightarrow$ interior or corner

## Proposition

*Assume that either $A \neq 0$ or $B \neq 0$. The optimal matching $\alpha^p$ is as follows:*

*(i) If $A \geq 0$, then $\alpha^p = 1$ if $A + B \geq 0$ and $\alpha^p = 0$ if $A + B < 0$;*

*(ii) If $A < 0$ and $B \leq 0$, then $\alpha^p = 0$;*

*(iii) If $A < 0$, $B > 0$, and $B + 2A \geq 0$, then $\alpha^p = 1$;*

*(iv) If $A < 0$, $B > 0$, and $B + 2A < 0$, then $\alpha^p = -B/2A \in (0,1)$.*

# Sorting and Inefficiency

## Proposition

*There is an equilibrium with PAM allocation while there is NAM in the planner's solution if and only if*

(*i*) $\mathcal{V}(X|\mu_+)$ *supermodular in* $X$*;*

(*ii*) $\mathcal{V}(\overline{X}|\mu_+) + \mathcal{V}(\underline{X}|\mu_+) - 2\mathcal{V}(\hat{X}|\mu_+) \leq 2[\mathcal{V}(\hat{X}|\mu_-) - \mathcal{V}(\hat{X}|\mu_+)]$

- Intuition:
  - "Supermodularity" (modified)
  - *Differential* externality NAM outweighs "supermodularity"
- Similar conditions for NAM equilibrium, PAM planner

# Sorting and Inefficiency

## Special Cases

1. Additively Separable Payoffs
   - $\mathcal{V}(X_i|\mu) = g(X_i) + h(\mu)$
   - $h(\mu_+) = \frac{1}{2}h(\overline{X}) + \frac{1}{2}h(\underline{X})$ and $h(\mu_-) = h(\hat{X})$
   - PAM equilibrium and NAM planner iff

$$g \quad \text{SPM and} \quad g(\overline{X}) + g(\underline{X}) - 2g(\hat{X}) \leq 2[h(\mu_-) - h(\mu_+)]$$

# Sorting and Inefficiency

## Special Cases

1. Additively Separable Payoffs
   - $\mathcal{V}(X_i|\mu) = g(X_i) + h(\mu)$
   - $h(\mu_+) = \frac{1}{2}h(\overline{X}) + \frac{1}{2}h(\underline{X})$ and $h(\mu_-) = h(\hat{X})$
   - PAM equilibrium and NAM planner iff

$$g \quad \text{SPM and} \quad g(\overline{X}) + g(\underline{X}) - 2g(\hat{X}) \leq 2[h(\mu_-) - h(\mu_+)]$$

2. Multiplicatively Separable Payoffs
   - $\mathcal{V}(X_i|\mu) = g(X_i)h(\mu)$
   - PAM equilibrium and NAM planner iff

$$g \quad \text{SPM and} \quad g(\overline{X}) + g(\underline{X}) - 2g(\hat{X}) \leq 2g(\hat{X})\frac{h(\mu_-) - h(\mu_+)}{h(\mu_+)}$$

   - Need $h$ 'sufficiently submodular' in $X$

# Uncertainty

- Many economic environments involve uncertainty
- Set up:
  1. Team composition $X_i$: labor market competition
  2. Team generates stochastic product $v_i$, from $F(v_i|X_i)$
  3. Output market competition $z(v_i, v_j)$
- Expected output $X_i$ : $V(X_i|X_j) = \int\int z(v_i, v_j) dF(v_i|X_i) dF(v_j|X_j)$

$$V(X_i|X_j) = \underbrace{z(\underline{v}, \underline{v}) + \int \frac{\partial z(v_i, \underline{v})}{\partial i} S_i dv_i + \int 2 \frac{\partial z(\underline{v}, v_j)}{\partial j} S_i dv_j}_{g(X_i)}$$

$$+ \underbrace{\int \frac{\partial z(\underline{v}, v_j)}{\partial j} S_j dv_j}_{h(X_j)} + \underbrace{\int\int \frac{\partial^2 z}{\partial i \partial j} S_i S_j dv_i dv_j}_{k(X_i, X_j)}$$

where $S_i = S(v|X_i) = 1 - F(v|X_i)$ is the survival function

# Economic Applications

I Knowledge Spillovers

II Oligopoly

III Policy and Sports Competitions

# I. Knowledge Spillovers

## Copying and the Evolution of Inequality

- Recent increase in inequality: between-firm inequality, not within-firm

  Card-Heinig-Kline (2013), Benguria (2015), Valchos e.a. (2015), Song e.a. (2016), Barth e.a. (2014)

- Model of knowledge spillovers (Romer-Lucas):
  - Type-dependent copying technology: Lucas-Moll (2014), Benhabib-Perla-Tonetti (2017), Eeckhout-Jovanovic (2002)
  - With an ex ante competitive matching stage

    $\Rightarrow$ Interior matching allocation

- Effect of increase in complementarity between workers

  $\Rightarrow$ Increase in fraction $\alpha$ of PAM matches

- Consistent with facts: between-firm inequality $\uparrow$ (of skills and wages)

# I. Knowledge Spillovers

## Copying and the Evolution of Inequality

- Two types $\overline{x}, \underline{x}$, equal measure. $X = x_1 + x_2$. Aggregate Spillover
- Stage 2: Firms choose investment $k$ to solve:

$$\mathcal{V}(X|\alpha) = \max_k \left( A(\lambda + H(k, X))k - \frac{k^2}{2X^\gamma} \right),$$

where $H(\cdot)$ is the CDF of all $k$ in the economy:

$$\begin{aligned} H(k, \overline{X}) &= 0 \quad \forall k, \\ H(k, \hat{X}) &= \begin{cases} 1 - \frac{\alpha}{2} - (1-\alpha) & \text{if } k \in [0, \overline{\kappa}) \\ 0 & \text{if } k \geq \overline{\kappa}, \end{cases} \\ H(k, \underline{X}) &= \begin{cases} 1 - \frac{\alpha}{2} & \text{if } k \in [0, \hat{\kappa}) \\ 1 - \frac{\alpha}{2} - (1-\alpha) & \text{if } k \in [\hat{\kappa}, \overline{\kappa}) \\ 0 & \text{if } k \geq \overline{\kappa}. \end{cases} \end{aligned}$$

- Stage 1: competitive labor market: $\frac{\alpha}{2}$ firms $\overline{X}$ and $\underline{X}$; $1-\alpha$ firms $\hat{X}$

### Proposition

*If $\lambda \geq 1$, $1 \leq \gamma < \overline{\gamma}$, and $\underline{x}/\overline{x}$ is sufficiently small, then there is a unique competitive equilibrium, which is interior (i.e., $\alpha \in (0,1)$). Moreover, the equilibrium $\alpha$ is strictly increasing in $\gamma$.*

- Calculate optimal $k^\star$ and the resulting $H(k)$
- Construct: $\Gamma(\alpha) = \mathcal{V}(\overline{X}|\alpha) + \mathcal{V}(\underline{X}|\alpha) - 2\mathcal{V}(\hat{X}|\alpha)$
- Apply Proposition above on interior solution and uniqueness
- $\frac{\partial \alpha}{\partial \gamma} > 0$: apply Implicit Function Thm to $\Gamma(\alpha; \gamma) = 0$

# I. Knowledge Spillovers

## Copying and the Evolution of Inequality

- Within firm variance across all firms: $\mathrm{Var}[w|\alpha^\star]$

$$\rightarrow \frac{\partial \mathrm{Var}[w|\alpha^\star]}{\partial \gamma} \approx 0$$

- Between firm variance: $\mathrm{Var}[w_i + w_j|\alpha^\star]$

$$\rightarrow \frac{\partial \mathrm{Var}[w_i + w_j|\alpha^\star]}{\partial \gamma} > 0$$

$\Rightarrow$ Increase in wage inequality: driven by between-firm variance; not within-firm variance

# I. Knowledge Spillovers

## Continuum of Types

- Winner-takes-all: externality increasing in $k$
- Objective: theoretical solution with continuum of types
- $x \sim U[0,1]$; $X = x_1 + x_2$ ($\gamma = 1$)
- Infinitely many matches, distributed $G(X)$:
    - PAM: $G(X) \sim U[0,2]$, or $G(X) = \frac{X}{2}$
    - NAM: all firms $(x, 1-x)$ so $X = 1$ and $G(X)$ mass point
- Stage 2 payoff function:

$$\mathcal{V}(X_i|\mu) = \max_{k_i} \left\{ AH(k_i,\mu)k_i - \frac{k_i^2}{2X_i} \right\}$$

- where $H(\cdot)$ is the distribution of $k$. FOC:

$$A[H + k_i H'] = \frac{k_i}{X_i}$$

- Consistency: $H(k_i) = G(X_i)$

# I. Knowledge Spillovers

## Planner – PAM

- Use $H(k_i) = G(X_i) = X_i/2$ (under PAM) to solve for $X_i$ in the FOC:

$$H(k_i) = \frac{k_i}{2A[H + k_i H']} \quad \Longleftrightarrow \quad H^2(k_i) + k_i H(k_i) H'(k_i) = \frac{k_i}{2A}.$$

- The solution to this differential equation is

$$H(k_i) \overset{c=0}{=} \sqrt{\frac{k_i}{3A}} \quad \text{and} \quad h(k_i) = \frac{1}{2\sqrt{3Ak_i}},$$

- Equilibrium investment $k_i^\star = \frac{3A}{4} X_i^2$ and payoff:

$$\mathcal{V}^\star = \frac{3}{32} A^2 X_i^3$$

- Welfare:

$$W_{PAM} = \frac{3}{32} A^2 \int_0^2 X_i^3 d\frac{X_i}{2} = \frac{3}{16} A^2.$$

# I. Knowledge Spillovers

## Planner – NAM

- Under NAM, $G(X_i)$ has a mass point:

$$G(X_i) = \begin{cases} 0 & \text{if } x < 1; \\ 1 & \text{if } x \geq 1. \end{cases}$$

- Conjecture a symmetric equilibrium where:

$$\mathcal{V}(X_i) = \begin{cases} Ak_i - \frac{k_i^2}{2X_i} & \text{if } k_i \geq k_{-i}; \\ -\frac{k_i^2}{2X_i} & \text{if } k_i < k_{-i}. \end{cases}$$

- NAM: continuum of allocations with $k_i \in [A, 2A]$
- The Pareto optimal solution $k^\star = A$ with $W_{NAM} = \frac{A^2}{2}$

⇒ Planner prefers Pareto optimal NAM over PAM

# I. Knowledge Spillovers

## Competitive Equilibrium

- PAM provided $\mathcal{V}^\star(x_i + x_j|\mu) = \frac{3}{32}A^2(x_i + x_j)^3$ supermodular in $x_i, x_j$ or

$$\frac{\partial^2 \mathcal{V}^\star(x_i + x_j|\mu)}{\partial x_i \partial x_j} = \frac{9}{16}A^2(x_i + x_j) > 0$$

- Wages

$$w(x) = \int_0^x \frac{9}{32}A^2(2s)^2 ds = \frac{3}{8}A^2 x^3$$

- NAM payoff $\mathcal{V} = \frac{A^2}{2(x_i+x_j)}$: not an equilibrium because supermodular:

$$\frac{\partial^2 \mathcal{V}^\star(x_i + x_j|\mu)}{\partial x_i \partial x_j} = \frac{A^2}{(x_i + x_j)^3} > 0$$

$\therefore$ PAM equilibrium; NAM Planner

# II. Oligopoly

- 2 firms; Linear demand $p = a - b(q_i + q_j)$, with $a > 0$ and $b > 0$, where $q_i$ and $q_j$ are the outputs of the two firms.
- Cost $C(x_k, x'_k, q_k) = c(x_k, x'_k)q_k$; cost-per-unit: $c(x_k, x'_k) = \nu - \beta x_k x'_k$, with $\nu > \beta \overline{x}^2$, $\beta > 0$; $c$ is strictly submodular, that is, $c_{12} = -\beta$, with "degree" of submodularity indexed by $\beta$.
- To ensure interior solutions we will assume that $a > 2c(\underline{x}, \underline{x})$.
- Nash equilibrium $q_i = (a - 2c(x_i, x'_i) + c(x_j, x'_j))/(3b)$with equilibrium price $p = (a + c(x_i, x'_i) + c(x_j, x'_j))/3$. The profits:

$$V(x_i, x'_i | x_j, x'_j) = \frac{(a - 2c(x_i, x'_i) + c(x_j, x'_j))^2}{9b} = \frac{(a - 2(\nu - \beta x_i x'_i) + \nu - \beta x_j x'_j)^2}{9b}$$

$$V(x_j, x'_j | x_i, x'_i) = \frac{(a - 2c(x_j, x'_j) + c(x_i, x'_i))^2}{9b} = \frac{(a - 2(\nu - \beta x_j x'_j) + \nu - \beta x_i x'_i)^2}{9b}$$

# II. Oligopoly

- MAtching PAM $\mu_+(x) = x$, ($\eta$ is PAM too)
- Equilibrium wages are equal to

$$\begin{aligned} w(x) &= w(\underline{x}) - \frac{4}{9b}\int_{\underline{x}}^{x} c_2(s,s)(a - c(s,s))ds \\ &= w(\underline{x}) + \frac{4\beta}{9b}\int_{\underline{x}}^{x} s(a - \nu + \beta s^2)ds \\ &= w(\underline{x}) + \frac{4\beta}{9b}\left((a-\nu)\frac{x^2 - \underline{x}^2}{2} + \beta\frac{x^4 - \underline{x}^4}{4}\right), \end{aligned}$$

# II. Oligopoly

- PAM equilibrium properties:

## Proposition

*If a is large enough, then there exists a competitive equilibrium with PAM. Wages increase in a and decrease in b, and firms with better composition of their labor force set higher markups.*

- Variance is increasing in $\beta$, the degree of supermodularity
  $\partial \text{Var}(w)/\partial\beta > 0$

# III. Policy and Sports Teams

- Sports competitions: US vs. Europe
  - US: intervention for balanced competition: PAM $\rightarrow$ NAM
  - Europe: laissez-faire: PAM
- We use the model with negative spillovers $z_i = v_0 + av_i + bv_j$
- Need to calculate wages
- Effects of policies:
  1. Taxes
     - Suitable taxes for hiring same type changes PAM to NAM
  2. Salary Cap
     - Bound on wage of high type cannot change PAM to NAM
  3. Rookie Draft
     - Senior types hire rookies
     - Sequential hiring at *fixed* type dependent wages: low senior types first
     - Equilibrium with NAM
     - Both senior types prefer it to PAM

# Conclusion

- Many output markets have externalities

⇒ How does it affect labor market? Assortative matching w/ externalities

- Unlike standard (Becker) matching problem:
    1. Solution can be interior
    2. Multiple equilibria possible
    3. Allocation generically ineffecient
    4. If inefficient: drastic, discontinuous reallocation
- Applications:
    - Knowledge spillovers: explain within/between-firm inequality
    - Oligopolistic output markets
    - Policy interventions

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