# The Locus of Innovative Capability: Learning and Forgetting in Biotechnology Research

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# Motivation

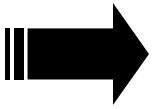
KNOWLEDGE

INNOVATION

# Innovative Capability

**DEFINITION**

Innovative capability is the knowledge a firm uses to innovate



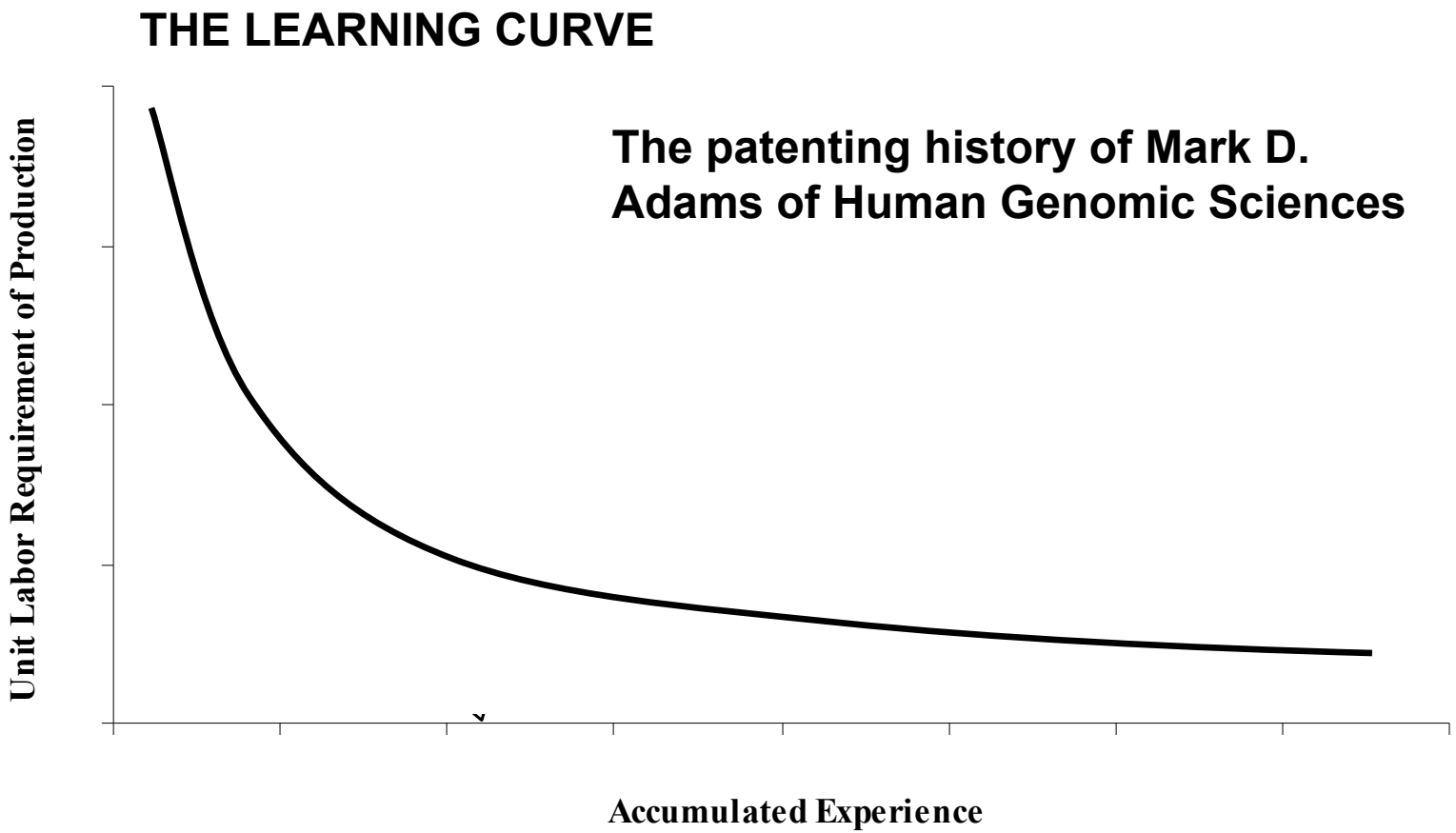
**QUESTIONS**

Accumulation?

Depreciation?

Locus?

# Learning curve and innovation

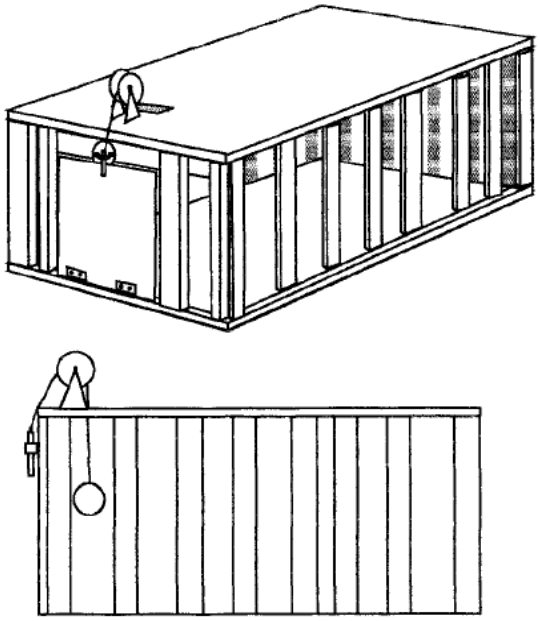


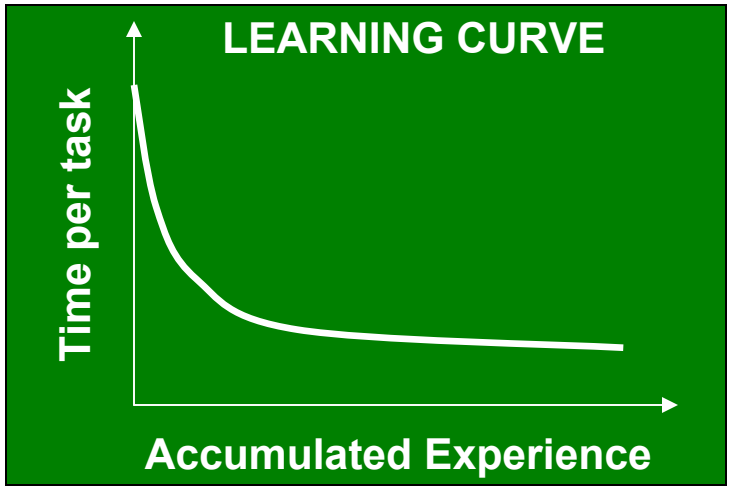
# Outline

- Motivation
- Theory
- Model
- Data
- Econometrics
- Results
- Discussion
- Conclusions

# The Learning Curve

- Experiments in individual learning (Thorndike 1898; Thurstone 1919)

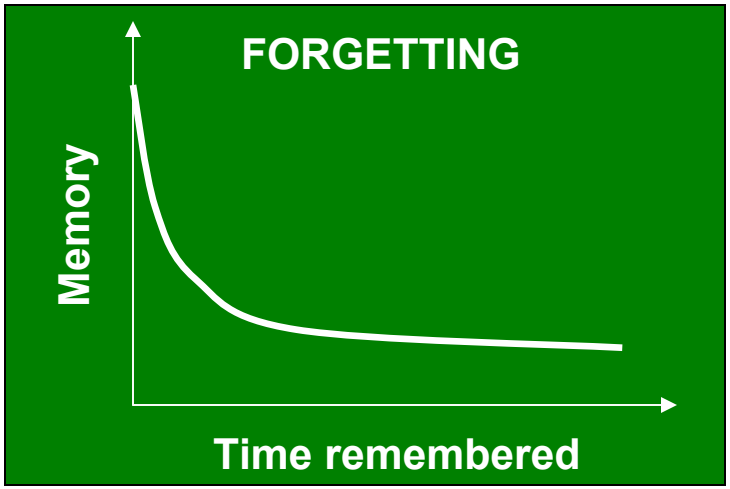





- **Organizations**
  - Unit costs of airframe manufacturing decline with accumulated experience (Wright, 1936)

# Forgetting

- Self experiments of memory (Ebbinghaus 1885)

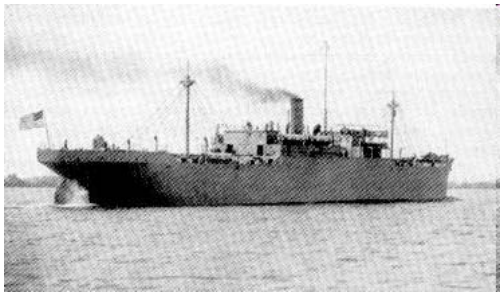




- **Organizations**
  - Accumulated experience is forgotten (Argote et al. 1990)

# Learning-Forgetting Studies

SS John W. Brown (Liberty Ship)

Lockheed L-1011



SS Mary Luckenbach
(Hog type Liberty Ship)

- Forgetting (Argote et al. 1990)
- Incomplete spillovers (Benkard 2000)
- Aggregation bias (Thompson 2007)

**Incomplete knowledge spill over & aggregation bias are important effects for innovation**

# Learning to Innovate

- **A Learning Curve in innovation is not evident**
  - **No blueprint for an innovation**
    - No two innovations are identical
    - Less routine and repetitive
    - Varying inputs and outputs

# Learning to innovate

- **Production possibility set (Nelson & Winter 1982)**
  - Knowledge is input, and also produced as output
  - R&D experience influences productivity
    - (Henderson and Cockburn 1994)
  - "Innovative Capacity" of a country is a function of the total stock of knowledge in an economy
    - (Furman, Porter and Stern, 2002)

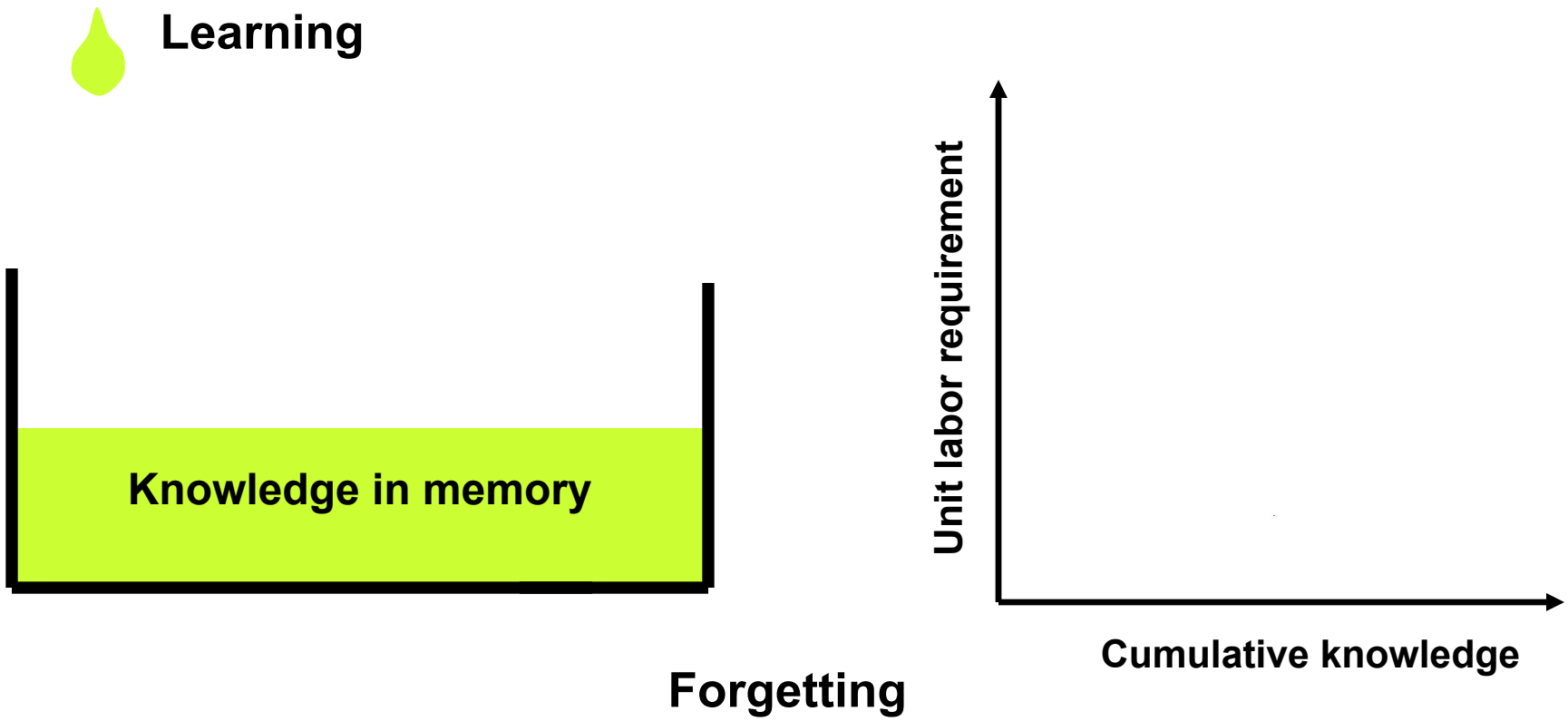
**Innovative capability is acquired by learning by doing, and a learning curve exists in innovation**

# Forgetting in innovation

- **Forgetting is the depreciation of accumulated innovative knowledge**
  - Turnover
  - Individual forgetting
  - Disruptions in innovative activity, such as switching from one domain of innovation to another

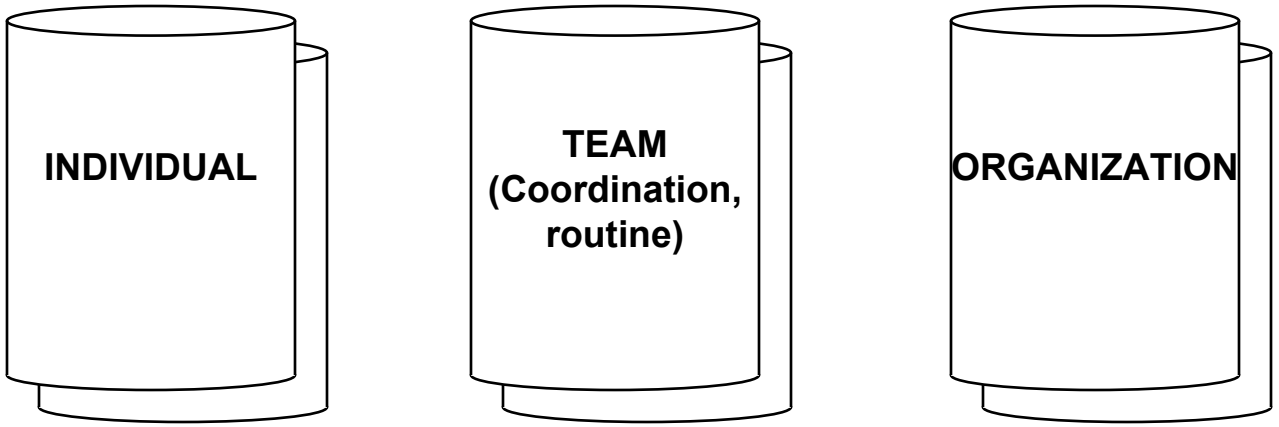
**Innovative capability depreciates over time and is forgotten**

# Innovative Productivity = f(learning, forgetting)



# Locus of Innovative Knowledge

(Levitt and March, 1988; Walsh and Ungson 1991)




**The locus of innovative capability is**

- **The individual**
- **Team coordination and routines**

# Mobility - Individual locus

- **Individual heterogeneity**
  - Mobile individuals take with them their skills and experience
    - (Boeker 1997; Rao and Drazin 2002)
  - Mobility leads to regional spillovers of knowledge
    - (Almeida and Kogut 1999; Song, Almeida, and Wu 2003)

**Hiring of skilled scientists leads to learning and to greater productivity, and their turnover leads to forgetting and to lower innovative productivity.**

# Mobility – Team locus

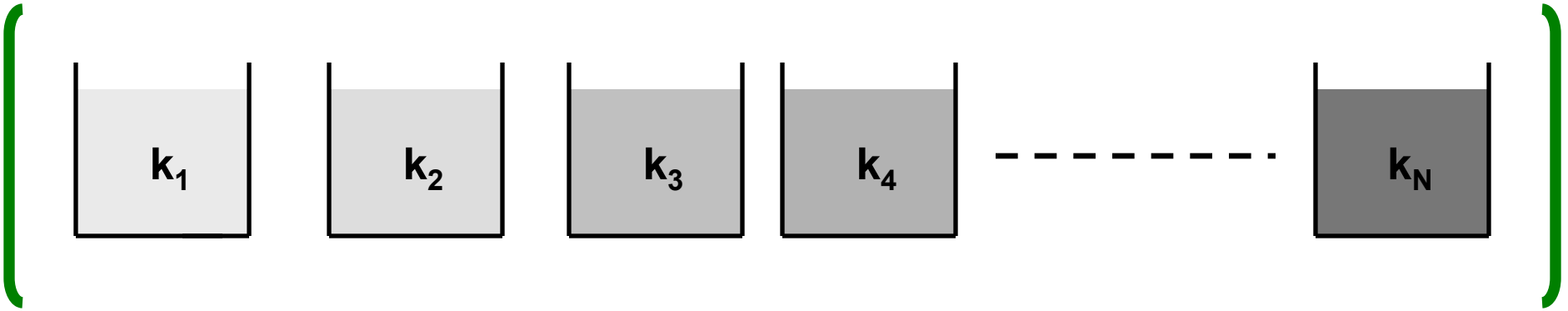
- **Team Coordination and Routines**
  - Silicon Valley Law Firms (Phillips 2002)
    - Turnover → Higher Mortality
    - Recruitment → Lower Mortality
  - Dutch Law Firms (Wezel, Cattani, and Pennings 2006)
    - Group turnover amplifies this effect
  - **Recruitment is also disruptive**
    - E.g. introduction of new scientist in a team

**Inbound and outbound mobility disrupts team coordination and routine in an organization, and results in lower the innovative productivity.**

# Model of Knowledge

## Innovation uses knowledge in many categories

**Vector of knowledge** (Cowan, Jonard & Zimmerman, 2007)




Individual knowledge: $I_{ti} = \langle I_{ti1}, I_{ti2}, .., I_{tij}, ...I_{tiN} \rangle$

# Innovations are heterogeneous

- **Innovation project requirements**
  - 0 → technology category is not used
  - 1 → technology category is used

→ $A_k = \langle A_{k1},\ldots, A_{kj},\ldots, A_{kN} \rangle \qquad A_{kj} \in \{0,1\};\ j \in [1, N]$

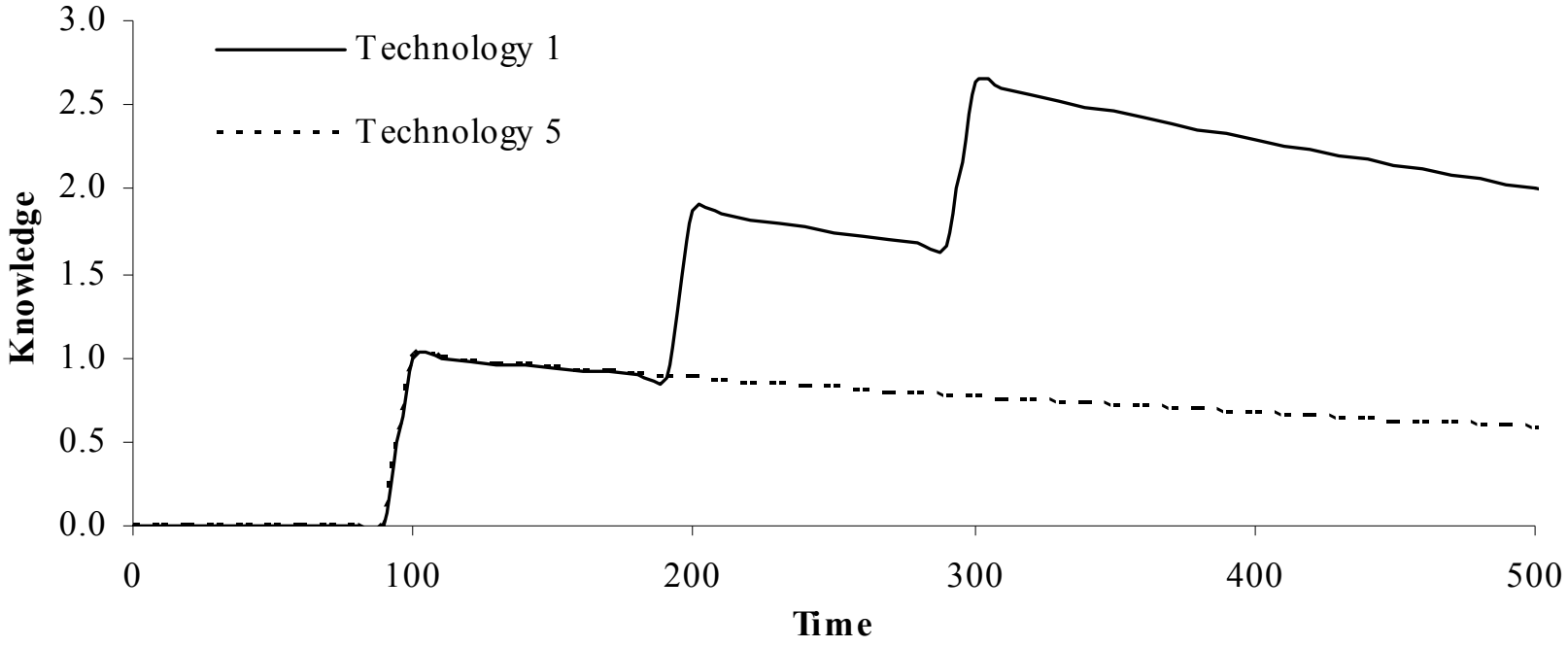
- **Knowledge used to innovate**

→ $Knowledge_{t_k i} = K_{t_k i} = I_{t_{k-1} i} A_k^T = \langle I_{t_{k-1} i1},..,I_{t_{k-1} ij},...I_{t_{k-1} iN} \rangle \langle A_{k1},\ldots, A_{kj},\ldots, A_{kN} \rangle^T$

# Knowledge accumulation and depreciation

$$\begin{cases} I_{0ij} = 0 \\ I_{t_k ij} = A_{kj} + e^{-\delta(t_k - t_{k-1})} I_{t_{k-1} ij}, \quad \delta \in [0,1], \quad t_{k-1} < t_k \end{cases}$$

**Learning, Forgetting, and the Evolution of Technological Knowledge**



# Learning curve

- **Learning curve specification** (Grilliches 1979)

$$q_k = \beta_f K_{t_k k}^{\lambda} C_{t_k}^{\alpha} L_{t_k}^{\gamma} S_{t_k}^{\beta} e^{\rho Z_{t_k}} + \upsilon_{t_k}$$

  - Taking logs, empirically test

$$\ln(q_\tau) = \ln \beta_f + \lambda \ln K_{t_k} + \alpha \ln C_{t_k} + \gamma \ln L_{t_k} + \beta \ln S_{t_k} + \rho Z_{it_k\beta} + \varepsilon_{t_k}$$

# Dataset and constructs

- **US and Canadian Biotechnology industry**
  - Knowledge intensive industry
  - Innovation is documented
  - Mobility has a important role (Zucker and Darby, 1996)

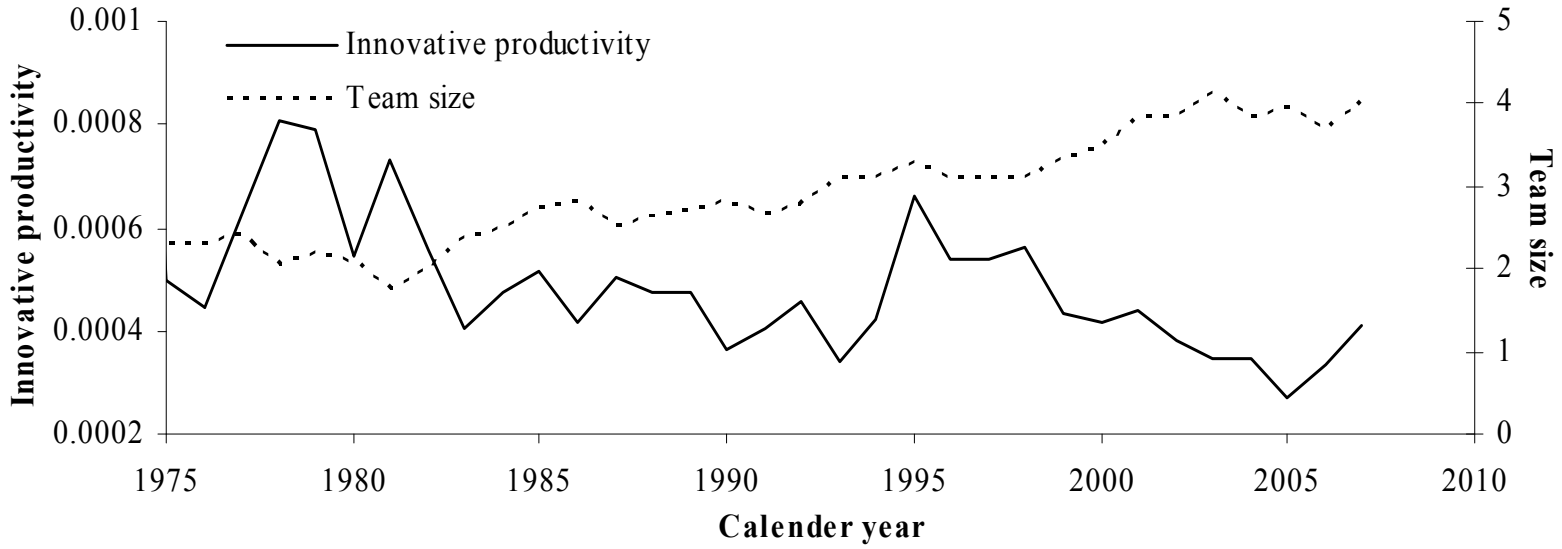
- **Data set**
  - Biotechnology firms from Capital IQ, Bioscan
  - Innovation data from USPTO
  - 38 years of data from 1970-2007
    - 25,318 patents
    - 611 firms
    - 20,886 scientists

# Dependent Variable

- Innovative Productivity
  - Unit labor requirement (ULR) = time in days taken to innovate

$$\text{Innovative productivity} = \frac{1}{\text{ULR}} = \frac{1}{\sum_{i=1}^{n} t_i}$$

**Innovative productivity and team size**



# Independent Variables

- **Knowledge**
  - Individual, organization
  - Team Coordination and Routines

- **Mobility**
  - **Hires**
    - Proportion of new hires
    - Hire knowledge
  - **Separations**
    - Proportion of separations
    - Separation knowledge

# Control Variables

- **Team**
  - Size
  - Prior productivity
  - Cumulative output
- **Firm**
  - Size (Capital)
  - Prior productivity
  - Cumulative output
  - Age
- **Industry**
  - Industry cumulative output
- **Patent**
  - Technological progress
  - Technological contributions (claims)
  - Complexity

# Modelling individual and organizational knowledge

- The hierarchical structure of USPTO Technology Classification System enables categorization

**Table 4. The system of indentation present in USPTO technology classes**

| Class/ Subclass | Indent | Description |
|---|---|---|
| 435 | | Chemistry: Molecular biology and microbiology |
| 173.1 | | Treatment of micro-organisms or enzymes with electrical or wave energy (e.g., magnetism, sound waves, etc) |
| 173.2 | • | Enzyme treated |
| 173.3 | • | Modification of viruses (e.g., attenuation, etc.) |
| 173.4 | • | Cell membrane or cell surface is target |
| 173.5 | •• | Membrane permeability increased |
| 173.6 | ••• | Electroporation |
| 173.7 | •• | Lytic effect produced (e.g., growth enhancement or increased production of microbial product) |
| 173.8 | • | Metabolism of micro-organism enhanced (e.g., growth enhancement or increased production of microbial product) |
| 173.9 | • | Concentration, separation, or purification of micro-organisms |

Class

Subclass

**Indent**

•

••

•••

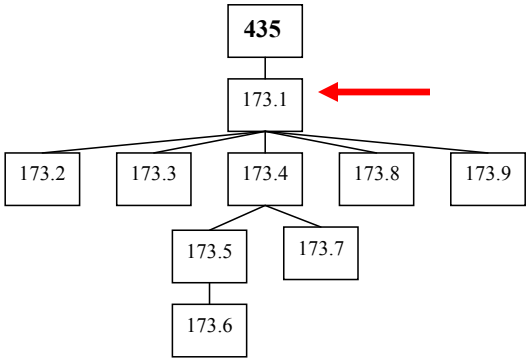



**Table 5. Technology class hierarchy and the number of subclasses[a]**

| Level | No. of distinct subclasses |
|---|---|
| 0 | 471 |
| 1 | 14,541 |
| 2 | 48,164 |
| 3 | 92,042 |
| 4 | 125,099 |
| 5 | 143,296 |
| 6 | 151,444 |
| 7 | 154,706 |
| 8 | 156,161 |
| 9 | 156,767 |
| 10 | 157,000 |
| 11 | 157,094 |

[a]Level 0 = primary class; level 1 = mainline subclass

- **Categories used by scientists = 3,748**
- **In biotechnology = 1,613**

# Econometrics

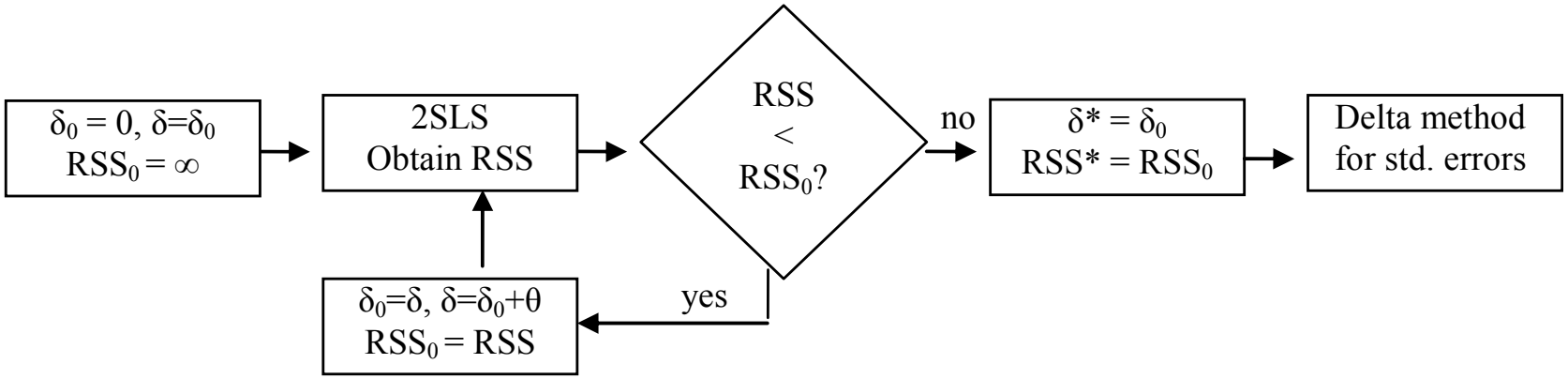
- **2 stage least squares regressions using panel data**

- **Instruments**
  - For firm and team cumulative output
    - Demand shifters (GDP per capita, GDP change from WDI)
    - Cost shifters (Employment cost index, US Dept. of Labor)

- **Firm fixed effects**
- **Year dummies**

- **Grid search for forgetting rate**
  - The forgetting rate is determined which results in best model fit
  - Standard errors are computed for this forgetting rate

**Grid Search for Forgetting Rates**

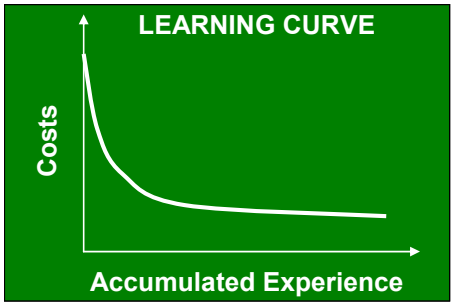


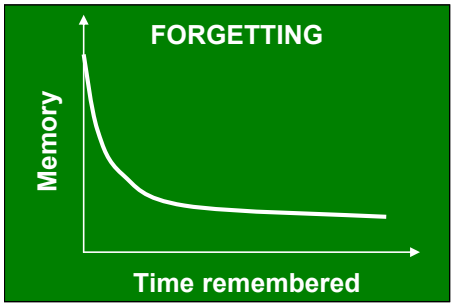
# Empirical Analysis

- **Step 1.** Replicate Argote's Study for Innovation
- **Step 2.** Locus of Innovation
- **Step 3.** Mobility

# Results: 1. Organizational level analysis

| REPLICATING ARGOTE (1990) | |
|---|---|
| Ln(Organizational knowledge) | 0.30 (16.1) *** |
| Forgetting | 0.11 (34.8) *** |
| RSS (R-square within) | 54,018 (0.35) |

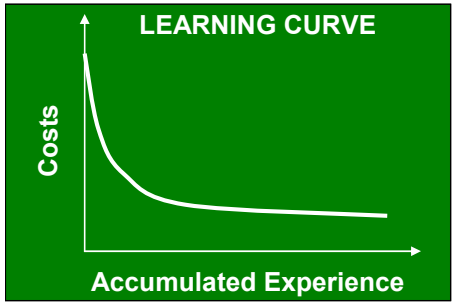


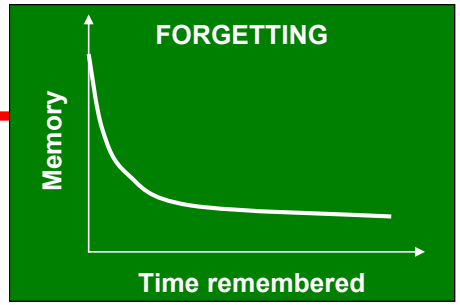



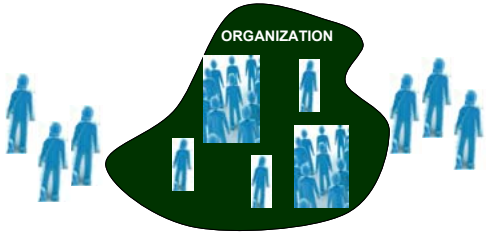

| Comparing results | | |
|---|---|---|
| | **Learning rate** | **Forgetting/month** |
| Argote (1990) | 0.33 to 0.41 | 0.25 |
| Organizational knowledge | 0.23 | 0.11 |

# Results: 2. Locus of innovative capability

| LOCUS | Individual Knowledge |
|---|---|
| Ln(Individual Knowledge) | 0.34 (20.7) *** |
| Forgetting | 0.02 (5.92) *** |
| Team Coord. & Routines | |
| Ln(Organization knowledge) | -0.04 (1.75) ^ |
| RSS (R-square within) | 41261 (0.51) |

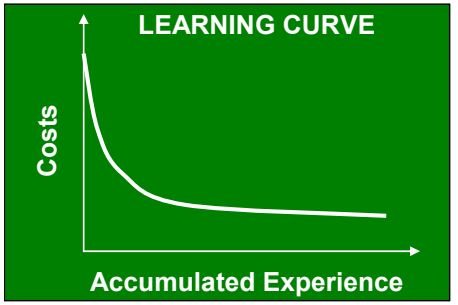


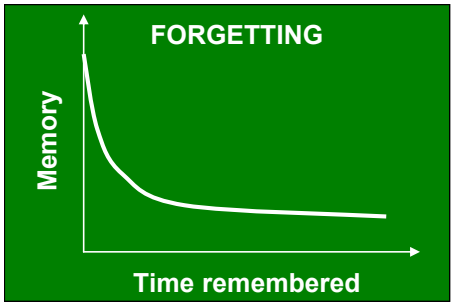



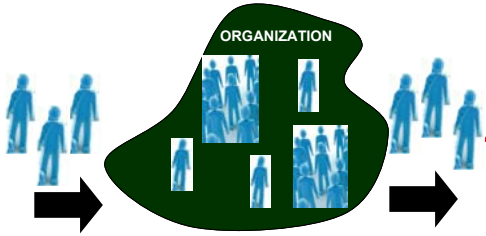



# Results: 3. Mobility

| MOBILITY | |
|---|---|
| Forgetting | 0.0132 (4.4) *** |
| Ln(Team Knowledge) | 0.34 (20.6) *** |
| Ln(Organizational Knowledge) | -0.04 (1.5) |
| Hires | -0.72 (2.4) * |
| Hire Knowledge | 0.01 (2.7) ** |
| Separations | 0.16 (0.69) |
| Separations Knowledge | -0.03 (2.2)* |
| RSS (R-square within) | 41564 (0.50) |

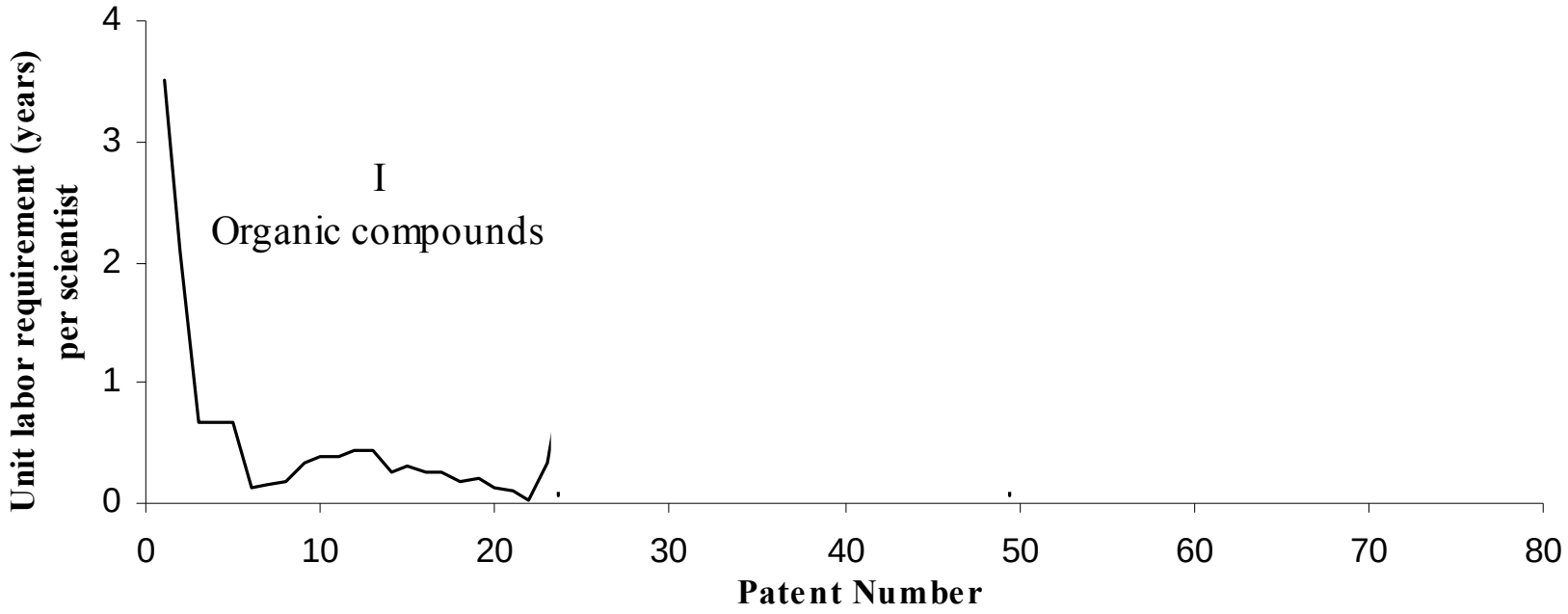


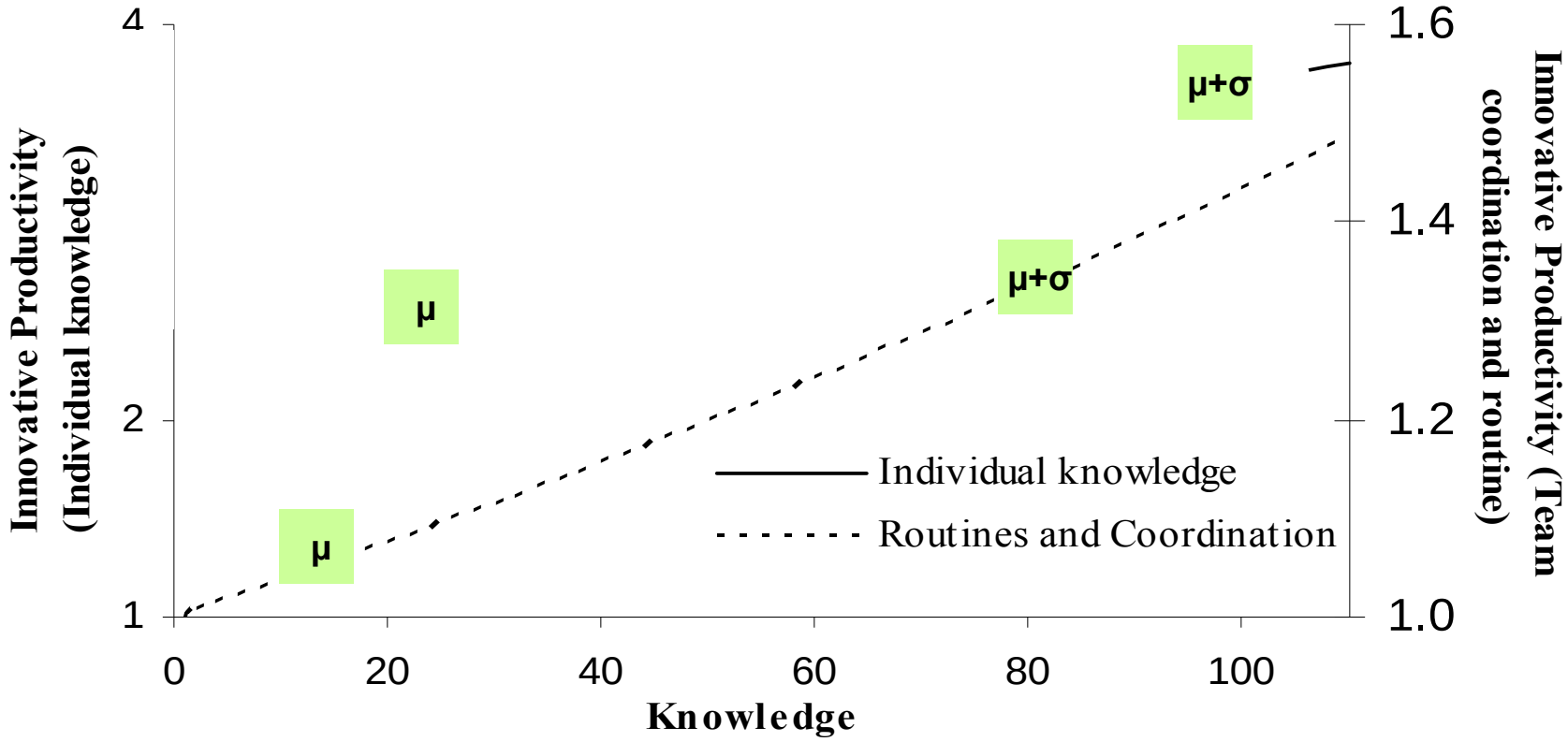
# Discussion: Individual knowledge and productivity

**Patenting by Mark D. Adams of Human Genomic Sciences**
Learning to Innovate in Different Technological Categories



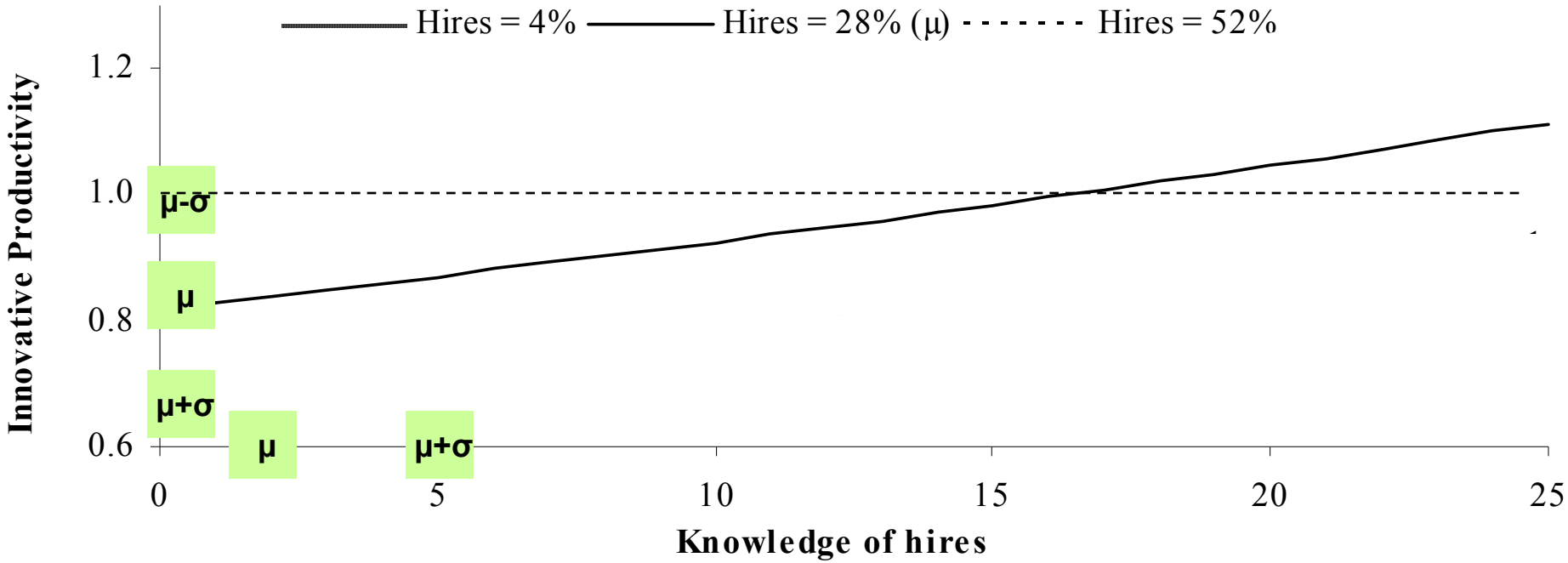
# Relative Effect of Coordination and Individual Knowledge

**The Influence of Individual knowledge is dominant relative to that of team coordination and routine**

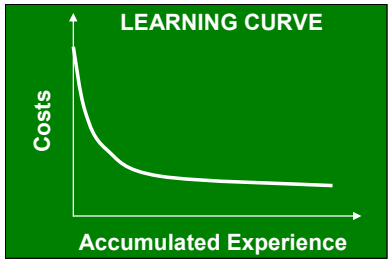


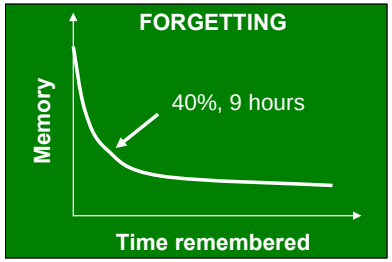
# Mobility: Coordination and Individual knowledge

**Figure 11. Hiring is disruptive in the short run.** But hiring few star scientists produce productivity gains



# Conclusions



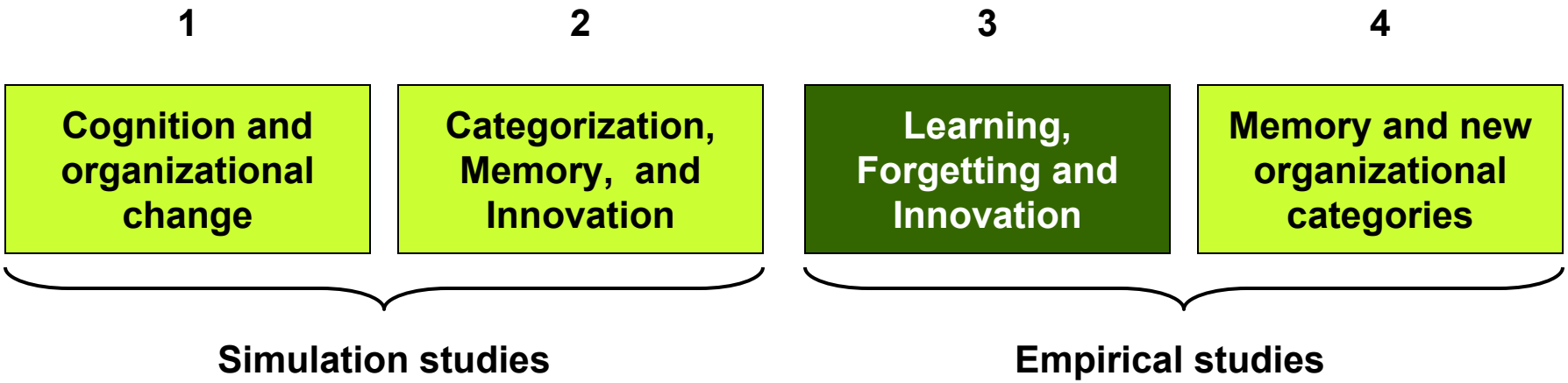





- **Innovation learning curve**
  - Innovative capability accumulates by learning by doing
- **Forgetting**
  - Innovative capability depreciates and is forgotten
- **Locus**
  - Individual = primary locus
  - Team Coordination and routines = secondary locus
- **Mobility**
  - Hiring is disruptive to coordination and routine
  - Hiring results in learning and to the acquisition of innovative capability

# Dissertation

**DISSERTATION: THE CATEGORIZATION OF KNOWLEDGE AND THE CREATION OF NEW COMBINATIONS**



# Future research with current database

- Why are certain organizations able to use their knowledge better than others?
- Why do organizations differ in their rate of learning and forgetting, and what competitive consequences does this have?
- Are social relationships also forgotten?
- What I know versus whom I know…

# THANK YOU!!!

**And a special thanks to a wonderful committee and chair!**

Karel COOL

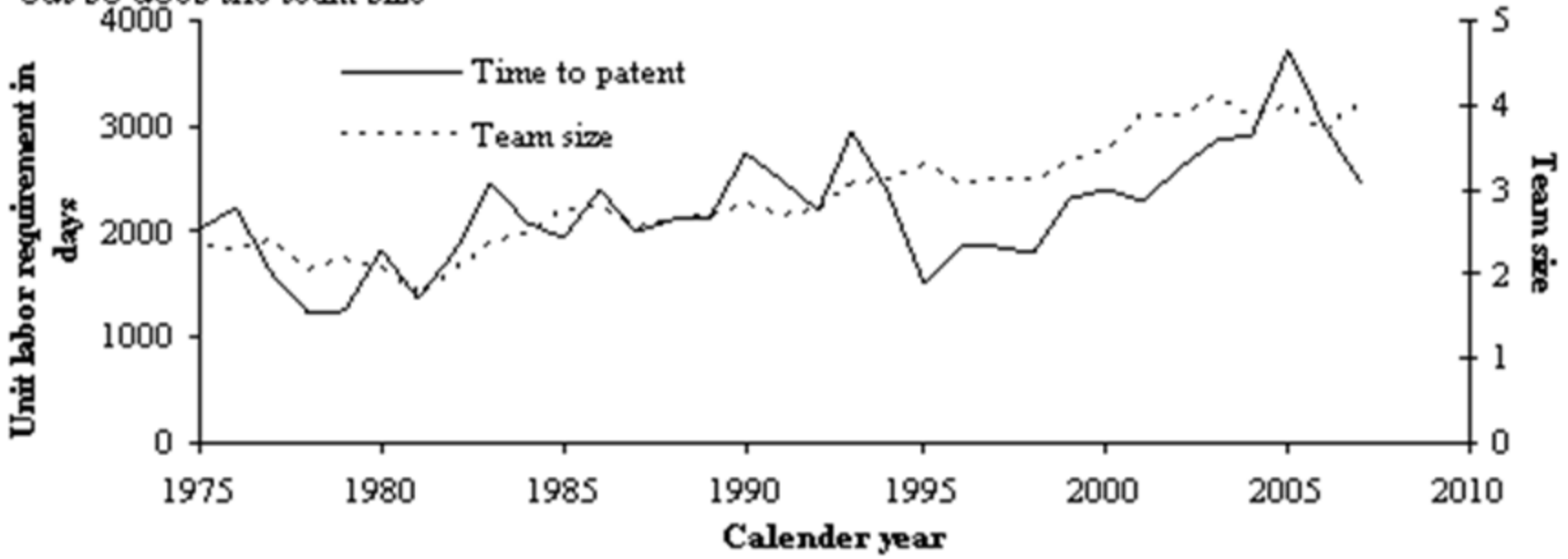
Bruce KOGUT (Chair)

Jasjit SINGH

Peter ZEMSKY

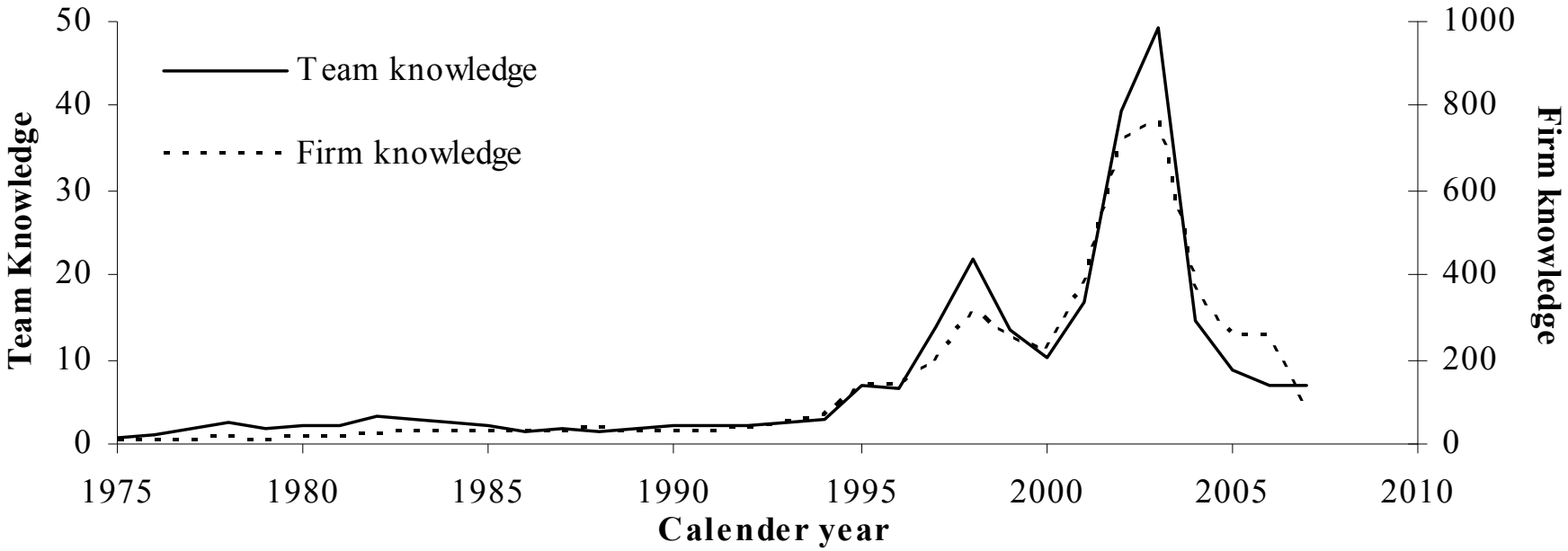
# Unit Labor Requirement of Innovation

**Figure 3. Innovative productivity.** The unit labor requirement of innovation increases over time, but so does the team size



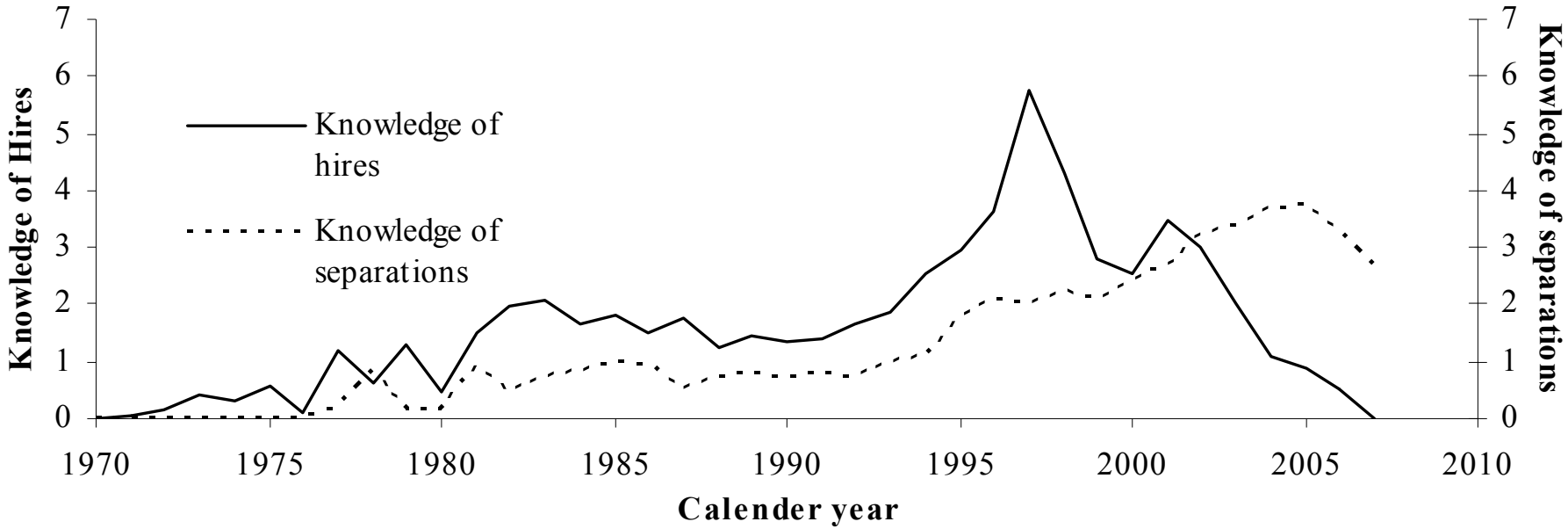
# Organizational and Individual Knowledge

## Team and firm knowledge are highly correlated



# The knowledge of mobile scientists

**Figure 8. The knowledge of recruited and separating scientists**



# Replicating Argote for Innovation

**Table 7. Replicating Argote's learning model for innovation.** Innovative productivity increases with organizational knowledge and decreases as this knowledge depreciates and is forgotten.

| | Controls | Experience | Prior productivity | Knowledge | Scope |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Forgetting (per month) | | | | 0.1131*** | 0.1219*** |
| | | | | (34.79) | (39.72) |
| ln(Firm knowledge) | | | | -0.2969*** | -0.2879*** |
| | | | | (16.06) | (16.44) |
| ln(Firm prior productivity) | | | -0.9498*** | -0.7623*** | -0.7869*** |
| | | | (20.35) | (27.53) | (28.41) |
| ln(Firm cum. output) | | -1.5536*** | 0.1125 | 0.2572 | 0.3300 |
| | | (6.25) | (0.50) | (0.79) | (1.59) |
| Scope | | | | | 1.9641*** |
| | | | | | (5.71) |
| Industry cum. output | -0.0383*** | 0.0287* | -0.0380** | -0.0374* | -0.0403* |
| | (5.57) | (2.24) | (3.28) | (2.29) | (2.46) |
| ln(Team size) | 1.3401*** | 1.2487*** | 1.2931*** | 1.6758*** | 1.5632*** |
| | (62.85) | (47.72) | (56.10) | (35.98) | (37.08) |
| ln(Firm capital) | -0.1186*** | 1.3044*** | 0.6077*** | 0.5458^ | 0.4700 |
| | (4.52) | (5.69) | (3.51) | (1.86) | (1.58) |
| Firm age | 0.0303** | 0.0870*** | 0.0026 | -0.0090 | -0.0093 |
| | (2.99) | (6.33) | (0.20) | (0.50) | (0.52) |
| Technological progress | 0.0004 | 0.0003 | 0.0001 | 0.0003 | 0.0004 |
| | (1.31) | (1.27) | (0.49) | (1.00) | (1.03) |
| Complexity | -0.0116^ | -0.0133* | -0.0108^ | -0.0135 | -0.0158^ |
| | (1.80) | (2.02) | (1.76) | (1.61) | (1.89) |
| Tech. contribution | 0.0046*** | 0.0044*** | 0.0043*** | 0.0039*** | 0.0039*** |
| | (6.16) | (5.78) | (6.05) | (4.03) | (3.99) |
| ln(A) | 5.3248*** | 4.7794*** | 4.7942*** | 4.6148* | 3.0061 |
| | (61.39) | (38.69) | (46.75) | (2.13) | (1.37) |
| Learning rate (1-p) | | | | 0.1860 | 0.1809 |
| RSS | 62427 | 64698 | 56351 | 54018 | 53818 |
| R-square (within) | 0.2522 | 0.2249 | 0.3249 | 0.3529 | 0.3553 |

**^ p < 0.10; p < 0.05; ** p < 0.01; ***p<0.001**

# Individual versus organizational knowledge

**Table 8. Team learning and forgetting.** The influence of organizational knowledge on innovative productivity disappears when team knowledge is introduced

| | Team Knowledge | | Firm and Team | Coordination and routines | Robustness |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Forgetting (per month) | 0.0263*** | 0.0231*** | 0.0198*** | 0.0231*** | 0.0231*** |
| | (13.44) | (6.25) | (5.95) | (5.57) | (5.42) |
| ln(Team knowledge) | -0.5996*** | -0.3202*** | -0.3431*** | -0.2848*** | -0.2800*** |
| | (27.74) | (17.80) | (20.75) | (16.80) | (15.37) |
| ln(Team prior productivity) | | -0.8208*** | -0.8247*** | -0.7582*** | -0.7602*** |
| | | (37.53) | (37.84) | (34.01) | (33.77) |
| ln(Team cumulative output) | | 0.1325*** | 0.1441*** | 0.1429*** | 0.1459*** |
| | | (5.72) | (5.91) | (5.96) | (6.22) |
| Coordination and routines | | | | -0.0036*** | -0.0036*** |
| | | | | (14.20) | (14.32) |
| ln(Firm knowledge) | | | 0.0472^ | 0.0472^ | 0.0439** |
| | | | (1.87) | (1.93) | (2.76) |
| ln(Firm prior productivity) | -0.7876*** | -0.2451*** | -0.2550*** | -0.1973*** | -0.1838*** |
| | (31.18) | (9.38) | (9.66) | (7.54) | (7.00) |
| ln(Firm cumulative output) | 1.0773** | 0.5315^ | 0.5119 | 0.2586 | 0.2019 |
| | (3.28) | (1.71) | (1.59) | (0.81) | (0.63) |
| Industry cumulative output | -0.0388* | -0.0196 | -0.0203 | -0.0072 | -0.0043 |
| | (2.51) | (1.35) | (1.41) | (0.50) | (0.30) |
| Scope | 2.5857*** | 2.0677*** | 2.0438*** | 1.7282*** | 1.6658*** |
| | (6.60) | (5.63) | (5.53) | (4.72) | (4.74) |
| ln(Firm capital) | -0.2875 | -0.1932 | -0.1929 | -0.0685 | -0.0299 |
| | (0.96) | (0.69) | (0.70) | (0.25) | (0.11) |
| ln(Team size) | 1.7172*** | 1.8067*** | 1.7744*** | 1.7806*** | 1.8180*** |
| | (40.26) | (41.27) | (30.62) | (31.45) | (39.34) |
| Firm age | -0.0581** | -0.0294^ | -0.0284^ | -0.0134 | -0.0115 |
| | (3.25) | (1.80) | (1.70) | (0.80) | (0.67) |
| Technological progress | 0.0004^ | 0.0003 | 0.0002 | 0.0005^ | 0.0005^ |
| | (1.68) | (0.85) | (0.77) | (1.67) | (1.74) |
| Complexity | -0.0418*** | -0.0207** | -0.0198** | 0.0180* | -0.0181* |
| | (5.27) | (2.80) | (2.69) | (2.47) | (2.46) |
| Technological contribution | 0.0022* | 0.0012 | 0.0012 | 0.0006 | 0.0007 |
| | (2.36) | (1.40) | (1.40) | (0.77) | (0.78) |
| ln(A) | 2.6711 | 3.1915^ | 3.1699^ | 3.3651^ | 3.4338^ |
| | (1.40) | (1.67) | (1.65) | (1.77) | (1.81) |
| Learning rate (1-p) | 0.3401 | 0.1990 | 0.2116 | 0.1791 | 0.1764 |
| RSS | 47647 | 41221 | 41142 | 40292 | 41158 |
| R-sq within | 0.4292 | 0.5062 | 0.5071 | 0.5173 | 0.5166 |

^ p < 0.10; p < 0.05; ** p < 0.01; ***p<0.001

# Mobility

**Table 9. Individuals and mobility.** Recruitment leads to learning, and turnover to forgetting.

| | | Characteristics of mobile scientists | | |
|---|---|---|---|---|
| | Proportion of staff mobile | Knowledge | Citations | Degree |
| | 1 | 2 | 3 | 4 |
| Hires | 0.5423^ | 0.6622* | 0.6407* | 0.8872** |
| | (1.87) | (2.20) | (2.19) | (2.90) |
| Hire knowledge | | -0.0189** | -0.0209** | -0.0170* |
| | | (2.76) | (2.93) | (2.37) |
| Hire cites | | | 0.0007^ | 0.0006^ |
| | | | (1.87) | (1.70) |
| Hire degree | | | | -0.0836*** |
| | | | | (4.71) |
| Separations | 0.0591 | -0.0485 | -0.0495 | -0.4643 |
| | (0.28) | (0.22) | (0.23) | (1.28) |
| Separation knowledge | | 0.0420 | 0.0400 | 0.0322 |
| | | (1.50) | (1.42) | (1.15) |
| Separation cites | | | 0.0003 | 0.0001 |
| | | | (0.28) | (0.09) |
| Separation degree | | | | 0.1012** |
| | | | | (2.61) |
| Forgetting (per month) | 0.0165*** | 0.0132*** | 0.0132*** | 0.0132*** |
| | (5.44) | (4.33) | (4.31) | (4.31) |
| ln(Team knowledge) | -0.3406*** | -0.3387*** | -0.3372*** | -0.3373*** |
| | (20.65) | (20.51) | (20.24) | (20.39) |
| ln(Team prior productivity) | -0.8266*** | -0.8205*** | -0.8176*** | -0.8147*** |
| | (32.25) | (32.31) | (32.44) | (35.03) |
| ln(Team cumulative output) | 0.1492*** | 0.1455*** | 0.1392*** | 0.1394*** |
| | (6.77) | (6.57) | (6.02) | (5.15) |
| ln(Firm knowledge) | 0.0436^ | 0.0435^ | 0.0425 | 0.0415 |
| | (1.67) | (1.67) | (1.61) | (1.53) |
| ln(Firm prior productivity) | -0.3717*** | -0.3795*** | -0.3864*** | -0.3791*** |
| | (13.14) | (13.40) | (13.61) | (13.29) |
| Scope | 1.9953*** | 1.9978*** | 1.9628*** | 1.8018*** |
| | (5.64) | (5.64) | (5.54) | (5.07) |
| ln(Firm cumulative output) | 0.8454* | 0.8946* | 0.9297* | 0.9250* |
| | (2.26) | (2.37) | (2.40) | (2.30) |
| Industry cumulative output | -0.0294* | -0.0314* | -0.0320* | -0.0336* |
| | (2.15) | (2.28) | (2.28) | (2.29) |
| ln(Firm capital) | -0.3394 | -0.3733 | -0.3881 | -0.0370 |
| | (1.20) | (1.31) | (1.34) | (0.12) |
| ln(Team size) | 1.7766*** | 1.7749*** | 1.7802*** | 1.7833*** |
| | (31.14) | (31.21) | (30.45) | (30.04) |
| Firm age | -0.0435* | -0.0439* | -0.0464* | -0.0440* |
| | (2.21) | (2.23) | (2.31) | (2.15) |
| Technological progress | 0.0003 | 0.0002 | 0.0002 | 0.0002 |
| | (0.85) | (0.01) | (0.81) | (0.72) |
| Complexity | -0.0198** | -0.0173* | -0.0170* | -0.0175* |
| | (2.71) | (2.34) | (2.27) | (2.34) |
| Contributions to knowledge | 0.0012 | 0.0012 | 0.0012 | 0.0012 |
| | (1.36) | (1.40) | (1.38) | (1.45) |
| ln(A) | 2.8832 | 2.8525 | 2.8590 | 2.9534 |
| | (1.48) | (1.49) | (1.46) | (1.51) |
| Learning rate (1-p) | 0.2103 | 0.2092 | 0.2084 | 0.2085 |
| RSS | 41429 | 41459 | 41491 | 41374 |
| R-square (within) | 0.5037 | 0.5033 | 0.503 | 0.5043 |

^ p < 0.10; p < 0.05; ** p < 0.01; ***p<0.001

# Organizational knowledge leads to bias

## Organizational knowledge constructs overestimate forgetting rates