Lecture # 6 -- Sources of Technological Change

I. Learning By Doing

- The models discussed last week look at the creation of knowledge by a deliberate inventive process.
- However, experience is also important.
  - Many product improvements are made by production workers, managers, and other users of technology.
  - Many things are unanticipated, such as:
    - Safety defects in airplanes
    - Bugs in computer software
    - Environmental consequences of chemicals
- <u>Learning by doing</u> is the acquisition of new skills, technology or processes that occurs during *the production process*. As a result, it takes place after a technological innovation has been adopted.
  - Involves acquisition of new skills, new processes, etc. in order to do something better.
  - These gains are internal to the production process.
  - Experience leads to the perception of possible improvements.
    - However, in addition to this perception, specialized knowledge, training, or skill is needed to carry out the improvements.
    - A negative relationship between unit production costs and cumulative output is one of the best documented empirical regularities in economics.
- Estimating learning curves
  - A learning curve regression:
    - Basic model: Cost = $a^*\mathrm{Cum}^{-b}$
      - Note that a is the cost at the start, when cum. production = 1.
    - $\log \mathrm{cost}_t = \log \mathrm{cost}_0 - b \log \mathrm{Cum}_t$
      - b is the *learning index*
      - 2^{-b} is the *progress ratio* – the relative price after a doubling of output
        - A progress ratio of 80% means the price is 80% of the original price after a doubling of output.
      - $1 - 2^{-b}$ is the *learning rate*.
        - In the above example, the learning rate is 20%. A doubling of output reduces costs by 20%

    - Issues estimating learning curves
        - Is it just the passage of time that matters?
            - Seems not to be the case
            - In regressions of the form $\log cost_t = \log cost_0 + b \log Cum_t + c\, t + error$, the coefficient on time is insignificant
        - Serial correlation
            - Will be an issue with two trends both changing over time (e.g. costs and cumulative output)
            - Part of the problem is that cost shocks lead to changes in input use
- Examples of learning by doing:
    - Liberty ships
        - During production of Liberty ships during WWII, increases in output led to decreases in labor requirements in all yards.
        - Did not occur due to design changes, as all the ships were the same.
    - Semiconductors
        - Semiconductor costs fall significantly as production experience (cumulative output) rises.
        - Exacting standards are needed for production.
            - Can be fine-tuned with experience.
            - For example, early in production, 90 of output may be flawed. With experience, this can fall to 10 percent.
        - A paper by Irwin & Klenow (1994) investigated whether there are spillovers to learning by doing, or do the benefits only fall on the originating firm?
            - Key findings:
                - Learning rates average 20% per year.
                - Firms learn three times more from increases in their own cumulative output, compared to another firm's cumulative output.
                - Learning spills over across countries.
                - There are few spillovers between successive generations of chips.
    - Renewable energy
        - There is evidence that renewable energy costs fall with experience.
        - Typical renewable energy market studies find learning rates around 15-20%.
        - Used as an argument for increasing deployment of renewable energy
            - But, need to know what caused the gains. Is it simply experience, or something more complicated?

- Are there potential limits to the benefits of learning by doing?
    - Motivation: if we make policy decisions assuming learning will occur, we need to know the limits to learning and the causal mechanisms (discussed next).
    - Is learning bounded?
        - First movers won't have infinite advantages if there are limits to learning
            - If so, having several smaller competitors, so that no one reaches the bounds, is better
        - If bounds are reached quickly, need other explanations for long-run improvements
        - Bounds are represented by the flattening out of the learning curve
    - Is learning uncertain?
        - There are a wide range of estimated learning rates (figure 1, p. 209)
        - Not clear what causes variation
            - Variation is found even when studying the same technology across plants or for different runs of a product in the same plant.
                - For example, two yards building Liberty Ships had faster learning.
                    - In one case, this plant started with lower productivity (e.g. poorer performance)
    - Factors influencing differences in learning over time or across plants
        - Largely "tacit" knowledge acquired through learning by doing depreciates with lack of use.
            - Tacit knowledge is not verbalized.
        - Depreciation may occur from large fluctuations in production, turnover of skilled workers, and strikes.
- As statistical association, learning by doing is not contentious
    - To be useful, however, there must be a causal connection
    - If learning simply comes from experience, then there is a market failure leading to low initial investment.
        - Early investors benefit others by providing experience, but they do not reap the benefits (or at least all the benefits) from future cost reductions.
        - However, if learning is really the result of other processes, then subsidizing early investment will not be enough to stimulate technological change.
    - Thus, an important question, however, is where these gains come from.

- Thomspon considers the same question addressing sources of learning
    - Thompson argues it is implausible that it is just an aggregation of worker learning, and thus just organizational in nature
        - Workers come and go
        - Provides an example (figure 6) of a producer of large magnets where costs increased, but then rapidly returned to expected trend, after large labor recruitment efforts
    - If it was just individual learning that mattered, could not have returned so quickly
    - Experience will be correlated with other variables important to productivity but unknown to the researcher
        - Higher base of installed capital
            - Increases in capital will correlate with increases in labor productivity
        - R&D expenditures
            - Sinclair, Klepper, and Cohen (2000) look at specialty chemical division of a Fortune 500 company
            - Have data on manufacturing costs, output, and chemical specific R&D expenditures
            - Estimated two sets of learning curves:
                - One for chemicals subject to formal R&D to improve the production process
                - One for chemicals with no formal R&D efforts to improve production, but were subject to a company-wide project to reduce amount of interim testing that took place during production
            - Significant learning found for nearly all chemicals in R&D group
            - In the informal R&D group, those in which testing costs were reduced have similar learning trends (albeit lower learning, about 1.04, rather than 1.2), but others do not
            - Suggest omitted variable bias from not including R&D
            - Do R&D and learning work together?
                - Might experience help firm target R&D where it would be most useful
                - Sinclair et al. say that R&D requests most often came from marketing and sales personnel after they identified large potential demand (e.g. forward looking)

- Nemet provides a detailed look at the sources of learning for photovoltaics.
    - Data is from 1980-2001
        - In that time frame, costs (measured as $/MW) have fallen by a factor of 7 ($25.3 $/MW to $3.68 $/MW – 2002 $'s).
        - Capacity is increasing at a rate of 40%/year
            - However, PV cells still only serve niche markets.
    - Concerns with learning curve models
        - Learning is a smooth, gradual process. Does not predict discontinuities that occur in the real world.
        - Industry-wide learning curves make assumptions about firms sharing experience.
        - Ignores changes in quality (e.g. costs may not fall, but quality may improve)
        - Disregards other sources of knowledge
    - To address these concerns, Nemet uses a regression to explain the falling costs of PV cells in this time period. The results are in Table 1 of the paper. Note that the model explains 95% of the cost savings in this period.
- Next, Nemet asks whether experience, measured by cumulative manufacturing production, can explain the most important factors.
    - Increased plant size
        - Explained primarily by growth in expected demand and improved risk management.
    - Module efficiency
        - Partly explained by learning by doing
        - However, most of the technical improvements came not from manufacturers, but from government and university R&D.
            - This was largely publicly funded R&D in the 1970s and early 1980s.
            - Cost reductions were a spillover from this funding.
        - Note that these institutions do not manufacture PV cells.
    - Learning by doing was important for four factors. However, these account for just 10% of the change in PV costs. They are:
        - Yield
        - Wafer size
        - Silicon consumption
        - Share of poly-crystalline silicon used
- Implications
    - Learning curves are not enough to predict cost changes
    - Thus, policy needs more than efforts to stimulate demand
        - Public research funding, policies to encourage spillovers (e.g. technology transfer) are also important

II. Incentives and the Research Process

- Up to this point, we have looked at the research process itself – *how* does research get done. In today's lecture, we look at factors that *influence* the research process.
    - In particular, we are interested in factors that influence the direction and level of effort devoted to research.
- Influences can be divided into two broad categories:
    - "Demand-pull" – innovation responding to the needs of the marketplace.
    - "Technology-push" – science provides new research opportunities that lead to new innovations.
- To begin, we consider a basic model of research and development. We will then look at how both supply and demand factors can affect this model.
- As is typical in economics, we'll assume that firms balance the marginal costs and benefits of doing R&D.
    - Marginal cost:
        - The marginal cost of R&D is the marginal cost of capital (MCC)
        - This is the opportunity cost of using capital for R&D, rather than other investments.
        - This is flat for a while (MC of $1 = $1), but eventually will slope up, as raising additional funds gets difficult.
            - At some point, can't simply use internal funds, but must raise debt externally.
    - The marginal benefit is the marginal rate of return (MRR). This is affected by:
        - Potential markets for the invention (demand-side influence)
        - Technological opportunities (supply-side influences)
            - These affect the likelihood that a research project will be successful.
        - Conditions affecting the appropriability of benefits (e.g. patents, the type of invention…)
- Note that, for now, we will focus on things that affect the MRR.
- Later, in the policy section of the course, we will consider policies that may affect MCC as well as MRR.

III. Demand-Pull Theories of Innovation

- Demand-Pull theories focus on the benefits that will come from a new innovation.

A. Induced Innovation

- Induced innovation is an example of a “demand-pull” influence.
- Induced innovation looks at the influence of factor prices on technological change.
  - E.g.: labor prices up => R&D to save labor
- Model
  - Begins with an innovation possibility curve (IPC).
    - The innovation possibility curve tells all the possible techniques that could be used at a given time.
    - Each possible technique is represented by an isoquant.
    - Note that we distinguished between *factor substitution* -- movement along an isoquant -- and *technological change* -- shifting to a new isoquant. Induced innovation asks what factors determine which new isoquants are developed.
  - Before any one technique is chosen, R&D must be performed.
    - The actual technology chosen depends on the relative prices.
  - One critique of the induced innovation model is that it assumes the IPC is given.
    - Shouldn’t changes in science and other fields affect the research opportunities?
- Evidence
  - Agricultural models:
    - Differences in land to labor ratios explain changes in farm technology across countries during the 19th and 20th centuries.
      - In the US, land was plentiful, but wages for labor were higher than elsewhere.
        - As a result, US farmers substituted capital for labor (e.g. farm machinery) in order to save labor.
      - In Japan, land is scarcer.
        - Thus, more fertilizer is used than in the US. This increases the productivity of the land.
  - Energy prices:
    - Patents related to new energy sources peaked in the late 1970's, when energy prices were highest.

B. Evolutionary Theory

- Evolutionary theory derives from work by Richard Nelson and Sidney Winter in the 1970s.
  - Arose from dissatisfaction of standard neoclassical economics to explain many empirical facts about long-run economic development and technological change.
- Key features of evolutionary theory:
  - Replaces profit-maximizing behavior of firms with decision rules applied routinely over a period of time.
    - Decision rules include routines for production, for managing workers, ordering inventory, advertising, or changing R&D.
  - R&D in evolutionary theory has two fundamental mechanisms
    1. Search for better techniques
    2. Selection of firms by the market
       - The term "evolutionary theory" is borrowed from biology. The idea is that the strongest firms survive.
       - Thus, profits matter, even though profit maximization isn't the explicit goal.
- The search process (see figure 2.3 in the Ruttan's article)
  - Searches take place if a firm is not satisfied with their current profits.
  - Searches are more likely to yield results close to the current technology (point A in the figure).
  - Once a search is concluded (point B), the firm decides whether or not the new technology is better.
    - In figure 2.3, B saves costs if prices are CD (labor is cheap), but not if prices are C'D' (labor is expensive).
    - *Intuition*: B is capital-saving. Doesn't make sense to use if labor is expensive.
      - If labor expensive, keep searching until find a point like B'.
- Note that these results are similar to the induced innovation theory. However, evolutionary theory has one important difference -- it is dynamic.
  - In the evolutionary model, invention is cumulative.
    - A successful search not only provides a new product, but also a new starting point for research.
    - After B is adopted, the next search will occur around the neighborhood of B.
    - Relating this to the induced innovation literature, this would suggest that the exact nature of *next year's* invention possibilities curve depends on the outcome of this year's research.

C. Path Dependence

- Path dependence depends on technology “lock-in.”
  - Once certain technologies are adopted, switching to a new technology might not be feasible, even if the new technology is marginally better.
- QWERTY typewriters are the classic example.
- Three features leading to QWERTY’s lock-in
  1. Technical interrelatedness – the need for system compatibility
     - In this case, the links are between the keyboard and the typist’s memory.
  2. Economics of scale – user costs fall as a system gains acceptance.
  3. Quasiirreversibility –the result of the acquisition of specific skills
     - In this case, touch typing skills.
     - Often the result of <u>network externalities</u>.
       - <u>Network externalities</u> are when an individual's demand depends on the consumption levels of other people.
       - Windows vs. Mac software is a good example of a network externality.
- This model applies to industries where network technologies lead to increasing returns to scale.
  - For example, it explains why a transition to hydrogen-powered vehicles will be difficult.
  - However, it does not apply more generally.

IV. Long Run Research Trends: The Importance of the Supply Side

- The models discussed above focus on demand for new innovations. They neglect the role that the *supply side*, or the state of scientific knowledge, plays in influencing research.
- The idea is that the basic knowledge on which other inventors can build is important.
    - As noted in the model above, the supply of new ideas increases technological opportunity.
        - This increases the likelihood of research success, and thus the marginal rate of return.
- Austrian economist Joseph Schumpeter noted the importance of long-run trends.
- The idea, as noted in the *Economist* article, is that “creative destruction” leads to waves of innovative activity.
    - Proprietary knowledge, as protected by patents or trade secrets, is valuable.
    - Thus, there is incentive to create new knowledge to reap these rewards.
    - New innovations make old ones obsolete. This is the notion of creative destruction.
- What Schumpeter noticed is that periods of great innovation occurred in waves:
    - Early 1800s: water power, textiles, iron (60 years)
    - Late 1800s: steam, rail, steel (55 years)
    - Early 1900s: electricity, chemicals, internal-combustion engine (50 years)
    - Late 1900s: petrochemicals, electronics, aviation (40 years)
    - 1990s-today: digital networks, software, new media (???)
    - What's next??: biotechnology, nanotechnology
- The *Economist* notes that the waves have been getting shorter.
    - One reason is that, in the early 20th century, governments and companies began to search for new technologies in a systematic manner.
    - Also, later innovations seem to build on existing ones.
        - Is the change from mainframe computers to PCs as drastic as the use of water power or steam engines?
- Connection to supply side:
    - Note that innovation peaks at the beginning of waves
        - New technologies open new doors for innovation.
        - Innovation slows down as diminishing returns set in.
- Evidence on the role of the supply side:
    - Energy patents:
        - In Popp (*American Economic Review*, 2002), I show that the number of energy patents in the US increased when energy prices were high.
            - However, patenting activity peaked before energy prices.
            - This is because of diminishing returns to R&D. Over time, there are fewer potentially new areas of research that can be exploited.
            - Thus, both demand and supply factors are important.

- Evidence from the surge in patenting
  - A paper by Kortum and Lerner (1998) argues that both increased technological opportunity and better R&D management, both noted as important above, led to increases in patenting in the 1990s.
  - They consider three hypotheses:
    1. Friendly-court hypothesis: As we'll discuss in greater detail soon, the development of the Court of Appeals of the Federal Court, which only dealt with patent cases, led to greater enforcement of patent rights.
       - If this led to more patenting, we should see more applications by both US inventors and foreign inventors in the US, but not more applications abroad.
       - The increase should be relatively uniform across technologies.
    2. Increased technological opportunities: New innovations result from discoveries in biotechnology, software, IT, and other new industries.
       - US patents should increase at home and abroad (if US main source of new innovations), or a general increase in patenting worldwide (if innovations are global).
       - May be technology specific.
    3. Changes in the management of R&D lead to increased productivity of R&D
       - Would also lead to an increase in patenting both at home or abroad, but will not be technology-specific.
  - Results:
    - The US has not increased as a destination for patents.
      - This rules out the friendly court hypothesis (1).
    - The increase has been worldwide.
      - There has been a recent improvement in the relative performance of US inventors worldwide.
      - There is no evidence these gains are concentrated among large firms, which might have suggested regulatory capture.
    - The gains seem to occur across technologies, suggesting that not only might there be increased technological opportunities (2), but also changes in R&D management (3).
      - Biotech and software patents have grown quickly, but there increase alone is not enough to explain the entire increase in patents.
    - Kortum/Lerner suggest the key management change is a shift towards more applied activities.