

Lecture 11: Endogenous Technological Progress

Christian Wolf

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Understanding TFP differences

- Solow and neoclassical growth model: A, g are exogenous.
- Data suggests:
 - Differences in A account for a large part of income differences across countries and for growth within countries over time.
 - These differences correlate with market structures, institutions, policies.
- Today: shed light on these patterns by studying models that allow for *endogenous* technological progress/endogenous long-run growth.
- Rich literature started by Paul Romer.
Significant contributions also by Robert Lucas, Philippe Aghion, Daron Acemoglu, and others.
- We will sketch the basic ideas and discuss some policy implications.

Outline

1. Towards endogenous growth: the AK model
 - Planner's solution
 - Competitive equilibrium
2. Background: determinants of technological progress
3. A model of endogenous growth with costly research
 - Fixed labor allocation
 - Optimal labor allocation
4. Ideas & government intervention
 - Intellectual property rights
 - Government intervention beyond patents

Prelude to endogenous growth: AK Model

- We now consider the simplest version of a model with “endogenous” long-run growth
- Objective is twofold:
 1. Emphasize role of linearity (= no diminishing returns) for possibility of persistent growth
 2. More practice solving planning problems and competitive equilibria
- Total output in the economy is given by

$$Y_t = AK_t,$$

where $A > 0$ is an exogenous parameter.

- In intensive (per-capita) form,

$$y_t = f(k_t) = Ak_t.$$

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Planner's solution

- The social planner's problem is the same as in the Ramsey model, except for the fact that output is linear in capital:

$$\begin{aligned} \max \quad & \sum_{t=0}^{\infty} \beta^t u(c_t) \\ \text{s.t.} \quad & c_t + k_{t+1} \leq f(k_t) + (1 - \delta)k_t \end{aligned}$$

- The Euler equation is

$$\frac{u'(c_t)}{u'(c_{t+1})} = \beta (1 + A - \delta)$$

- Assuming CES preferences, this reduces to

$$\frac{c_{t+1}}{c_t} = [\beta (1 + A - \delta)]^{\frac{1}{\theta}}, \quad \text{or} \quad \ln c_{t+1} - \ln c_t \approx \frac{1}{\theta} (A - \delta - \rho)$$

- Consumption growth is proportional to the difference between the real return on capital and the discount rate.
- Note that now the real return is a constant, and not diminishing with capital accumulation.

Planner's solution

- The resource constraint can be rewritten as

$$c_t + k_{t+1} = (1 + A - \delta)k_t.$$

- As before this completes characterization of the equilibrium in the sense that we've arrived at two difference equations.
- But now we can actually say a lot more.
 - Since total resources (the RHS of the above) are linear in k , an educated guess is that optimal consumption and investment are also linear in k .
 - We thus propose

$$c_t = (1 - s)(1 + A - \delta)k_t$$

$$k_{t+1} = s(1 + A - \delta)k_t$$

where the coefficient s is to be determined and must satisfy $s \in (0, 1)$.

- Can we verify this guess?

Planner's solution

- Under our guess

$$\frac{c_{t+1}}{c_t} = \frac{k_{t+1}}{k_t} = \frac{y_{t+1}}{y_t} = s(1 + A - \delta)$$

so that consumption, capital and income all grow at the same rate.

- From the Euler equation we also get this growth rate as $[\beta(1 + A - \delta)]^{\frac{1}{\theta}}$. Thus to ensure perpetual growth we need

$$s(1 + A - \delta) > 1 \quad \text{or} \quad [\beta(1 + A - \delta)]^{\frac{1}{\theta}} > 1$$

- But let's first of all verify the guess ...

Planner's solution

- We can re-write the resource constraint as

$$\frac{c_t}{k_t} + \frac{k_{t+1}}{k_t} = (1 + A - \delta),$$

implying that the consumption-capital ratio is given by

$$\frac{c_t}{k_t} = (1 + A - \delta) - [\beta (1 + A - \delta)]^{\frac{1}{\theta}}$$

- Using $c_t = (1 - s)(1 + A - \delta)k_t$ and solving for s we conclude that the optimal saving rate is

$$s = \beta^{\frac{1}{\theta}} (1 + A - \delta)^{\frac{1}{\theta} - 1}.$$

Same as on the previous slide, as it should be ...

- Note that the saving rate is increasing in the real return if and only if the EIS is higher than unity, and vice-versa. $s = \beta$ for $\theta = 1$.

Planner's solution

- Finally, to ensure $s \in (0, 1)$, we impose

$$\beta^{\frac{1}{\theta}} (1 + A - \delta)^{\frac{1}{\theta} - 1} < 1.$$

- Holds as soon as $\theta \geq 1$ and $\beta (1 + A - \delta) > 1$, as then $s = \beta^{\frac{1}{\theta}} (1 + A - \delta)^{\frac{1}{\theta} - 1} \leq \beta < 1$.
 - But when $\theta < 1$, this puts an upper bound on A . If A exceeded that upper bound, then the social planner could attain infinite utility, and the problem is not well-defined.
- Summary: the economy grows perpetually and constantly.
 1. Is the same also true in the competitive equilibrium? And what does that competitive equilibrium look like?
 2. What are the broader lessons for long-run growth?

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The competitive economy

- There is a large number of competitive firms with access to the AK technology. The eq'm rental rate of capital and the wage rate are then simply given by $r = A$ and $w = 0$. Make sure you see why. Clearly, the prediction $w = 0$ is unrealistic and tells us that the model is missing something important. But let's move on ...
- Households save in capital (return $r - \delta$) and bonds (return R). Arbitrage dictates that $R = r - \delta = A - \delta$.
- The Euler equation for the representative household gives

$$\frac{c_{t+1}}{c_t} = [\beta (1 + R)]^{\frac{1}{\theta}} = [\beta(1 + r - \delta)]^{\theta}$$

- Following the same steps as in the standard neoclassical growth model, we conclude that the competitive market allocations coincide with the Pareto optimal ones. Why? private and the social return to capital coincide, so prices yet again coordinate perfectly.

The competitive economy

Proposition

Consider an AK economy with CES preferences and suppose that the parameters $(\beta, \theta, A, \delta)$ satisfy $\beta (1 + A - \delta) > 1 > \beta^{\frac{1}{\theta}} (1 + A - \delta)^{\frac{1}{\theta} - 1}$. Then, the equilibrium is Pareto optimal (and so coincides with the planner's solution) and the economy exhibits a balanced growth path. Capital, output, and consumption all grow at a constant rate, which is given by

$$\frac{k_{t+1}}{k_t} = \frac{y_{t+1}}{y_t} = \frac{c_{t+1}}{c_t} = [\beta (1 + A - \delta)]^{\frac{1}{\theta}} > 1.$$

Consumption and investment are given by

$$c_t = (1 - s) (1 + A - \delta) k_t \quad \text{and} \quad k_{t+1} = s (1 + A - \delta) k_t.$$

where $s = \beta^{\frac{1}{\theta}} (1 + A - \delta)^{\frac{1}{\theta} - 1} \in (0, 1)$.

Revisiting the role of policy and institutions

- Note: the predictions of the neoclassical growth model about steady state level effects of (A, δ, β) are now recast as predictions about long-run *growth rates*.
- Minor extension: let there be a tax on income/saving at rate τ , similarly to what we did in the neoclassical growth model earlier. [Make sure you could derive this ...]
 - The equilibrium is not Pareto optimal anymore, exactly as before.
 - The equilibrium growth rate is now given by

$$\frac{y_{t+1}}{y_t} = [\beta (1 + (1 - \tau)A - \delta)]^{\frac{1}{\theta}} > 1.$$

which is now decreasing in τ .

- **Bottom line:** differences in technology, preferences and institutions may thus explain differences not only in the steady-state level of output (as in Solow/Ramsey), but also in the rate of long-run growth.

Beyond AK

- In the rest of today's lecture we will consider richer endogenous growth models that achieve two goals:
 1. Provide a deeper understanding of the process of technological growth (positive), shifting focus in particular to the accumulation of new knowledge
 2. Shed further light on reasons of inefficiency in market allocations (normative), thus also opening the door to interesting policy implications
- Big picture: why was the AK model a useful start?
 - Down the line we will want to treat “A” as something that is accumulated, like capital.
 - Our analysis has revealed that, for this to generate long-run growth, we can't have diminishing returns to “A”. We somehow need linearity.

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What determines technological progress?

- Technological progress (or TFP growth) is driven by ideas.
- In our context: ideas capture new ways of combining capital and labor, and organizing the production process.
- But where do new ideas (or innovation) come from?

Where do ideas come from?

1. **Learning by doing:** ideas are by-product of other activities.
 - Motivating example: workers in early factories learned how to use machines (experience + process innovation)
 - Very simple theory: this is just a positive externality, so simple policy prescription is just to subsidize the idea-generating activity.
 - Arguably more important at early stages of development. Don't develop the iPhone as a side-product of actually doing something else.

Where do ideas come from?

2. **Costly research:** idea production requires resources/effort, or R&D.
- Did iPhone come about for free as a side-product of producing iMacs, or by deliberate **R&D effort** by Apple? Are research papers written for free as a by-product of teaching or with effort/time?
 - Resources allocated to produce ideas could be utilized elsewhere. So **idea production is a form of (costly) investment**
 - In our model: take away time (L) from production and put it into augmenting A instead

Where do ideas come from?

- 3. **Knowledge spillovers:** ideas are generated by science/past ideas.
 - Newton: “If I have seen further it is by standing on the shoulders of Giants.”
 - May provide a strong amplification mechanism. Also means that there are externalities not internalized by markets, or that gov't should subsidize research, especially basic research
 - But it still requires the research is purposeful and takes effort. So it's more of an extension/side-product of 2.
- **Next:** consider a stylized model to capture forces 2. and 3. ...
 - First, treat the allocation of resources to R&D as given and study how it matters
 - Then, understand incentives that determine how many resources are allocated to R&D

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Consider resource allocation to research

- Suppose labor is allocated between production and research:

$$L = \underbrace{L_Y}_{\text{labor engaged in production}} + \underbrace{L_A}_{\text{labor engaged in idea production}} .$$

- Understand the effects of this in an environment that is as simple as possible:
 - For now ignore complications about optimal savings—just fix s , i.e. Solow model.
 - Make the model even easier: $n = 0$ so that $L_t = L$.
 - Assume the split of labor is exogenous. Will later see how it's chosen optimally.
- **Q:** what are the effects of the split of L into L_Y and L_A when L_A feeds into A ?

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Researchers increase A , with spillovers

- As before, we have the labor-augmenting technology:

$$Y(t) = K(t)^\alpha (A(t) L_Y)^{1-\alpha}.$$

- **Growth of $A(t)$ now depends on labor in research:**

$$\dot{A}(t) = z \times L_A \times A(t)$$

- We assume that more labor increases the *growth rate* of technology rather than the *level*.
- This is exactly the linearity assumption that we need for persistent growth. May be justified via knowledge spillovers.

Summary of our model

- As said, for simplicity, we first suppose people save at a constant rate, s . We will consider the proper Ramsey problem version of this later.
- With this assumption, our model becomes:

$$Y(t) = K(t)^\alpha (A(t) L_Y)^{1-\alpha}$$

$$\dot{K}(t) = sY(t) - \delta K(t)$$

$$\dot{A}(t) = zL_A A(t).$$

- Does this model remind you of anything?

Solow with “endogenous” tech. progress

- Note that the last equation implies:

$$\frac{\dot{A}(t)}{A(t)} = \underbrace{zL_A}_{\text{define this to be } g}.$$

- Then, the **model is identical to Solow** with g given by zL_A and labor force L_Y .
- Only difference is that g is now “**endogenous**”: depends on L_A .
- What do we know about the behavior of this model?

Key: linear equation for A , no diminishing returns

Solving the model with technological progress

- Recall that we defined capital per effective labor:

$$k(t) = \frac{K(t)}{A(t) L_Y},$$

- We have shown $k(t)$ converges to k^* where:

$$sf(k^*) = (\delta + g)k^*.$$

- Using $f(k) = k^\alpha$, we can explicitly solve $k^* = \left(\frac{s}{\delta+g}\right)^{1/(1-\alpha)}$.

Solving the model with technological progress

- Note that aggregate capital and output are given by:

$$K(t) = k(t) A(t) L_Y$$

$$Y(t) = f(k(t)) A(t) L_Y = F(K(t), A(t) L_Y)$$

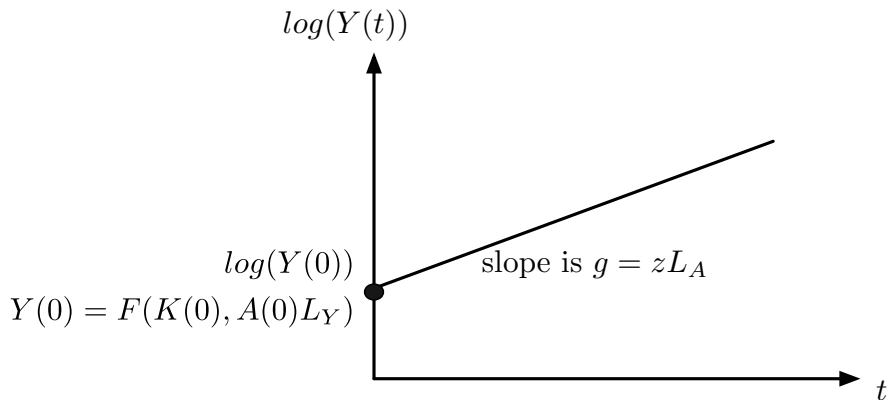
- Starting with $k(0) = k^*$, the economy is on a balanced growth path. Aggregate capital and output grow at rate $g \equiv zL_A$.
- Starting with $k(0) \neq k^*$, there are transitional dynamics to the balanced growth path. This is all exactly how we've already discussed it.

How does more research affect output?

- Let us use this model to analyze the effect of research on the output path.
- Consider an economy that is initially on the balanced growth path with some L_Y, L_A division of its total labor.
- The next slide visualizes the output path starting with some $K(0), A(0)$, and keeping the L_Y, L_A division unchanged.
- The subsequent slides investigate the effect of switching to more research.

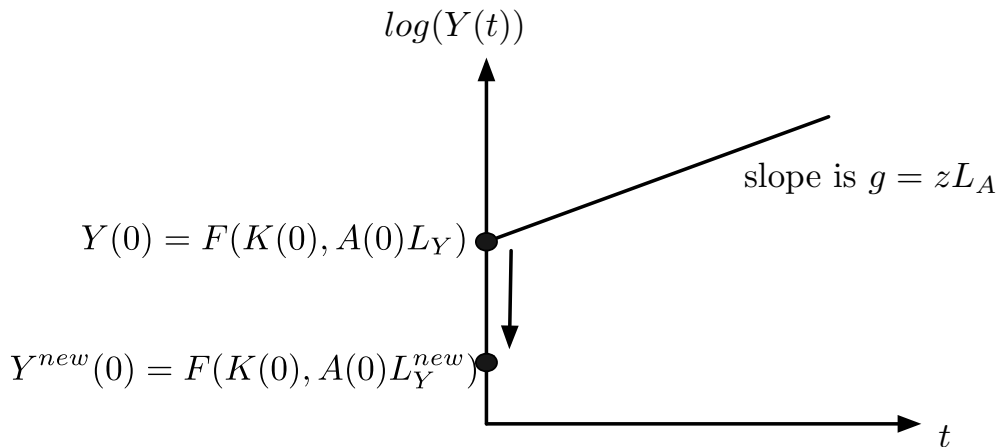
Starting point

The economy is initially on a balanced growth path:



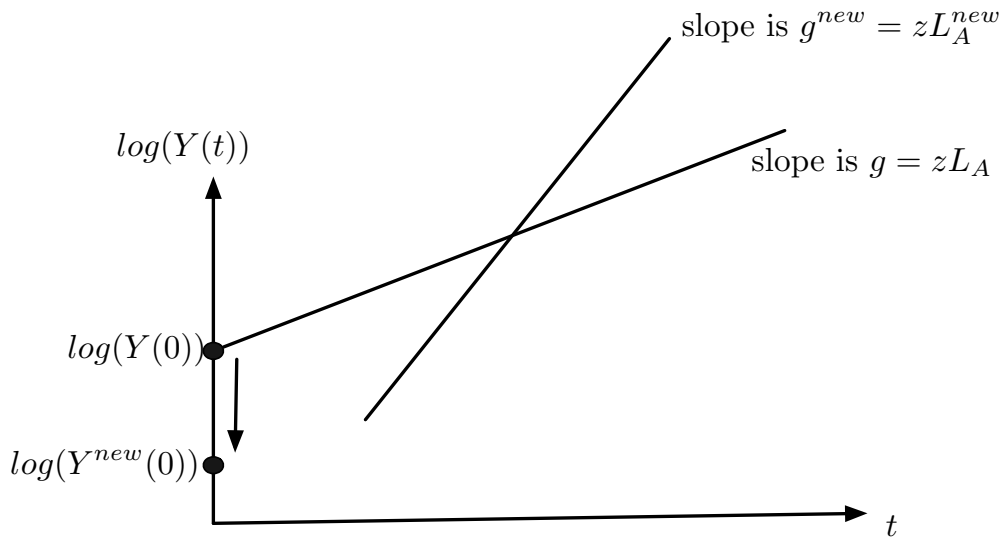
Now suppose, at date $t = 0$, the economy switches to $L_A^{new} + L_Y^{new} = L$ with $L_A^{new} > L_A$.
What happens to output in the short run (at $t = 0$)?

Switch to more research: short run

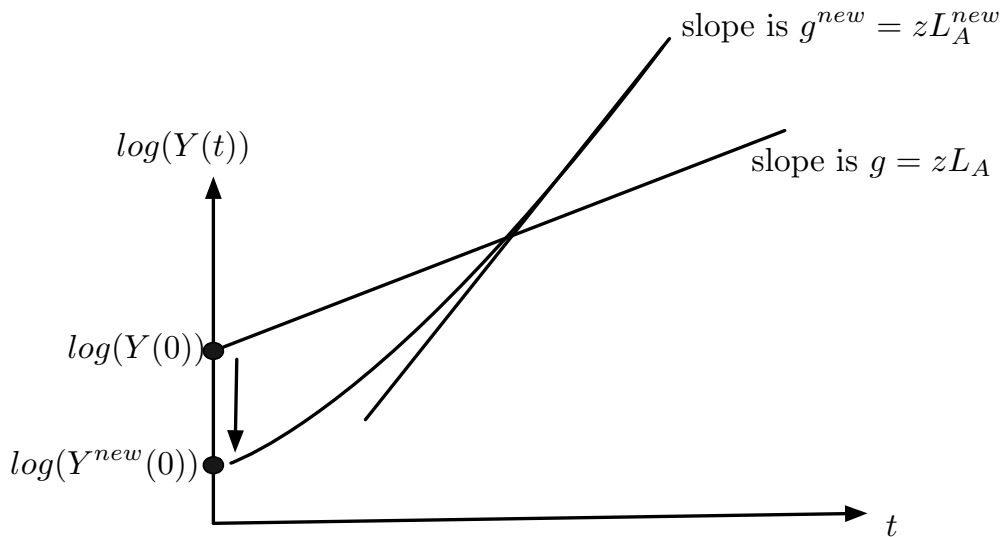


At time of switch, output necessarily falls. Why? How about the long run?

Switch to more research: long run



Switch to more research: transition dynamics



Research: trade-off between now and future

- Switching to $L_A^{new} > L_A$ reduces current output/consumption. Resources allocated to research as opposed to production.
- But it increases future output/consumption.
- Does this remind you of any trade-off we have seen before?

Research is similar to saving/investment

- This is like consumption-savings in the neoclassical model! Intuitively, research is also a form of investment. It is investment in ideas as opposed to capital.
- It is influenced by similar forces. So if we truly endogenized L_A from incentives, we could expect it to go together with s .
 - Romer (1990) endogenizes L_A . See Section 3 of the Scientific Background to the Nobel prize posted on Canvas.
 - Any factor that raises s is likely to raise L_A .
 - What were some factors that raise s ? Preferences, technologies, taxes, distortions, etc.
- Now: *optimal* allocation of labor & savings

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Environment

- We now turn to determining the optimal split between L_Y and L_A . For this we will first consider the problem of a benevolent social planner.
- Objective function is as usual

$$\sum_{t=0}^{\infty} \beta^t u(c_t)$$

- Total labor is fixed at 1. Denote the share assigned to production at time t by $\eta_t \in [0, 1]$, so $L_Y(t) = \eta_t$, $L_A(t) = 1 - \eta_t$. Total production is

$$y_t = a_t f(k_t, \eta_t)$$

Technology evolves as

$$a_{t+1} = [1 + \gamma(1 - \eta_t)]a_t$$

Planner's problem

- We can now state the full planner's problem:

$$\max_{\{c_t, k_{t+1}, \eta_t, a_{t+1}\}} \sum_{t=0}^{\infty} \beta^t u(c_t)$$

subject to

$$\begin{aligned} c_t + k_{t+1} &= a_t f(k_t, \eta_t) + (1 - \delta)k_t \\ a_{t+1} &= [1 + \gamma(1 - \eta_t)] a_t \end{aligned}$$

together with initial conditions $\{a_0, k_0\}$.

- In the standard problem we faced a trade-off between c_t and k_{t+1} . Now there is a second trade-off: between producing and generating more ideas.
- Let $\beta^t \lambda_t$ and $\beta^t \mu_t$ denote the multipliers on the two constraints.
 - Remember: λ_t is the value of an additional dollar of output.
 - Similarly: μ_t is the value of an additional unit of technology

Planner's problem

- The first two optimality conditions—for c_t and k_{t+1} —should look familiar:

$$\begin{aligned}u'(c_t) &= \lambda_t \\ \lambda_t &= \beta \lambda_{t+1} [a_{t+1} f_k(k_{t+1}, \eta_{t+1}) + (1 - \delta)]\end{aligned}$$

- The optimality condition for a_{t+1} is:

$$\underbrace{\mu_t}_{\text{cost of increasing } a_{t+1} \text{ at } t} = \beta \left[\underbrace{\mu_{t+1} (1 + \gamma (1 - \eta_{t+1}))}_{\text{higher } a_{t+2}, \text{ valued at } \mu_{t+1}} + \underbrace{\lambda_{t+1} f(k_{t+1}, \eta_{t+1})}_{\text{more output, valued at } \lambda_{t+1}} \right]$$

- The optimality condition for η_t is

$$\underbrace{\lambda_t a_t f_n(k_t, \eta_t)}_{\text{value of labor in production}} = \underbrace{\mu_t \gamma a_t}_{\text{value of labor in research}}$$

- Solution to these difference equations together with suitable boundary conditions is solution to planning problem.

Discussion

- The generation of ideas requires effort.
- From a planning perspective this gives rise to a trade-off: resources should be allocated optimally across production and ideas generation.
Conceptually this is identical to the consumption-savings trade-off.
- There is, however, one very important difference:
 - Remember that the planning problem is an artificial construct. We found it interesting because, for the consumption-savings trade-off, a simple competitive model implied the same allocation as the planning problem.
 - Ideas, however, are different from normal physical goods. The rest of this lecture note discusses just how exactly ideas are different.
 - We'll see that, because of these differences, a competitive economy would never reproduce the planning problem solution that we just derived. Suggests a role for gov't intervention.

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Nonrivalry and excludability

- Ideas have two very important properties:
 1. They are **nonrival**:
 - Rival: if I use this classroom, others can't simultaneously use it.
 - Nonrival: if I use the Solow model, others can also use it! I.e., we can replicate/share ideas at (almost) no cost.

This feature makes ideas different than other goods & capital.

2. We may still be able to **exclude** others from using our ideas.
- We will see that these two properties call for a unique role of the government in regulating research.

Nonrivalry of ideas

- To make the analysis concrete, consider the Pharma industry.
 - Say the cost of developing a new drug is about \$800 million. Once discovered, each dose of the drug costs \$10 to produce.
 - **The formula is nonrival:** all Pharma companies can use it.
- Suppose company *A* spends \$800 million and discovers the idea. But then we let all Pharma companies use the idea and produce.
- What would be the equilibrium price? Company *A*'s profits?

Nonrivalry creates an appropriability problem

- Competition would drive the price all the way down to \$10. Thus, in the extreme, profits of company A would be \$0.
- As a result, company A would be at a net loss of \$800 million!
- There is an **appropriability problem**: A would not undertake costly research, since it cannot appropriate profits from the idea.

Back to our model: this would imply that the private market sets $\eta_t = 0$, because investing in ideas never yields any profits.

- How can we solve the appropriability problem?
 - This is where excludability comes in.
 - Suggests a first role for government intervention.

Excludability & intellectual property rights

- Even though ideas are nonrival, they are also **excludable**.
- A might be able to prevent others from using the drug formula.
 - Excludability might come from **secrecy** (e.g., Coca-Cola's recipe)
 - It might also come from **expertise** (ideas are not easy to copy).
 - But excludability becomes particularly easy if we assign **property rights to knowledge**, making it more like capital.
- These are known as the **intellectual property rights (IPR)**.

Some real life examples: patents, copyright, trademarks ...

Benefits of IPR: improve appropriability

- A key benefit of IPR is to mitigate the appropriability problem:

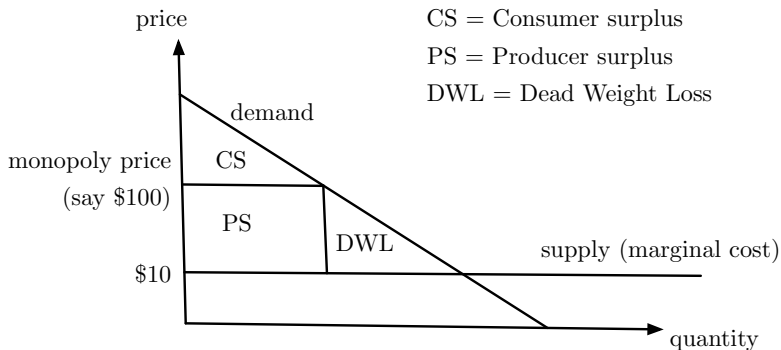
stronger IPR $\implies$ less competition/more appropriable $\implies$ higher L_A

- So perhaps we should have extremely strong IPR protection.
- How about strongly enforcing all patents forever? What are some problems with this policy prescription?

Costs of IPR: monopoly distortions

- Strong IPR might be good for technology **discovery**.
- But it's not necessarily good for **utilizing** technology most efficiently.
 - Strong IPR, e.g., patents, typically lead to **monopoly pricing**. Far away from the perfect competition we modeled earlier in this class.
 - Our story: company *A* with patent could charge \$100 per dose.
 - Many customers might be unable/unwilling to buy at this price.
 - This leads to a loss in social welfare (DWL in the next picture ...)

Costs of IPR: monopoly distortions



- Monopolist chooses price that maximizes PS.
- The social welfare from the drug is equal to $PS + CS$.
- The maximum social welfare is $PS + CS + DWL$ (with $p = \$10$).

Does stronger IPR always stimulate research?

- Our analysis so far suggests that stronger IPR stimulates research, at the cost of worsening utilization of discovered ideas.
- But even this conclusion would be too blunt.
 - Appropriability is important, but it is not the only determinant of costly research. Richer models feature various other forces.
 - Can you think of channels by which IPR might *stifle* research (while also worsening the utilization as described above)?

Further effects

- **Escape competition effect**

- Above, we viewed innovation as a one-time affair, and we focused on the market structure/competition after innovation is done.
- But in practice innovation happens repeatedly. The market structure can affect the incentives for **future innovation**.
 - Low current profits, but higher profits once you innovate.
 - Stronger IPR $\implies$ less current competition $\implies$ less research.
- If this effect is strong, then one could imagine intermediate level of competition (and/or intermediate IPR) might be better for research.

- **Availability/spillover effect**

- Weaker IPR $\implies$ previous advances could be widely available.
- Followers & future innovators could build upon the knowledge. This avoids wasteful replication, and can trigger new research.
- Firms with patents can “hold-up” industries, preventing further innovation by outsiders or competitors in the same industry.

Taking stock from intellectual property rights

- We've seen that IPR can influence research through several channels:
 1. **Appropriability:** IPR can stimulate research
 2. **Escape competition:** IPR can stifle further research.
 3. **Availability:** IPR can reduce idea availability/spillovers.
- Is the provision of IPR the only role that the government should play in the generation of ideas?

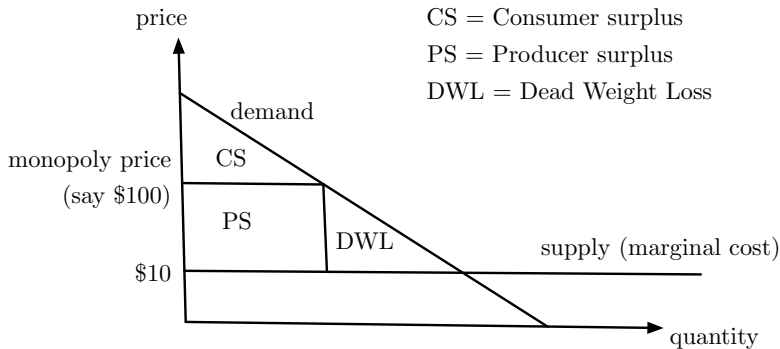
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Beyond patents

- In more recent years, government-funded research also seems to be an important direct driver of costly research (e.g., NSF/NIH).
- Should the government get directly involved in (costly) research?
 - Consider the baseline with a patent system in place. Is research too little from a social point of view? Or too much?
 - Do patents provide socially appropriate incentives?
 - Are incentives too strong? Are they too weak?

Consumer surplus effect: too little research



- Suppose PS (with optimal monopoly price) is \$700 million.
- Suppose PS+CS is \$1billion (adding DWL raises even further).
- Recall the cost of innovation is \$800 million. Does company A innovate? Why? Is it socially efficient to innovate? Why?

Consumer surplus effect: too little research

- Company *A* takes into account its profits, captured in the PS.
- But it does not take into account the CS.
 - CS can in principle be very high: Sick consumers might be willing to pay much more than the price, say \$1000.
 - But company *A* might not be able to extract this surplus.
- So patents, even if they are very strong (and work as intended), provide too little incentives for research.
- This is known as **consumer surplus effect**.

Knowledge spillovers: too little research

- Recall that we also have **knowledge spillover effect**
- Company A 's discovery makes future discoveries easier.
 - Company A takes into account immediate profit incentives.
 - But doesn't take into account benefits to other innovators.
- Does this lead to too much or too little research?

Creative destruction

- There is another factor that pushes in the opposite direction. New products/firms also tend to replace existing ones.

What did the invention of the iPhone do to Blackberry?

- So innovation/growth typically creates winners **and losers**. This feature of growth is also known as **creative destruction**.

First emphasized by the famous economist Joseph Schumpeter, modern modeling and further discussion by Aghion-Howitt, for the 2025 Nobel Prize.

- Central to a functioning capitalist economy: **every quarter, more than 10% of workers** in the US separate from their employers (either move to new job, become unemployed, or leave labor force).

Business stealing effect: too much research

- Creative destruction generates a **business stealing effect**.
- Social value of iPhone is not the value of a smartphone relative to no smartphone. Instead, it is incremental—having a “better” smart phone.
- But Apple’s incentives to innovate not necessarily incremental.
 - If better than Blackberry, might take the whole market!
 - Some of the profits (the PS) is simply transfers from Blackberry.
- Does this lead to too little or too much research?

So what is the optimal regulation of research?

- So we typically have several effects:
 1. Consumer surplus effect (too little research)
 2. Knowledge spillover effect (too little research)
 3. Business stealing effect (too much research)
- The net effect can in principle take either sign. But many economists believe 1+2 outweigh 3.
- Private incentives—even with patents available—tend to generate too little research. Provides a rationale for government subsidy of research.

Taking Stock

Summing up

- Endogenous growth from investment in research. The main trade-off similar to saving/investment in capital—consumption today vs. tomorrow.
- But raises new and interesting conceptual issues:
 - Nonrivalry of ideas and the appropriability problem.
 - Excludability of ideas and intellectual property rights.
 - Various competing effects of IPR on research activity.
- Overall the process of research is associated with several inefficiencies that create scope for government intervention/regulation.

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