Lecture 6: R&D as Search -- Options and Portfolios

RD is investment/search into the unknown that increases knowledge to bring you closer to a profitable payoff. But searching the unknown is risky – you don't know what you will get. To reduce risk you can treat the search as an option where you stop search if it is not promising.

1)Since you learn as you go, RD can be set up as a **sequential decision** and thus structured as a REAL OPTION. Optimal sequential decisions follow a **stopping rule** that says after some point you decide to proceed or stop and spend resources elsewhere. If you found the fountain of youth, stop R&D and jump in. If your R&D has not led you closer to your goal, kill the project and try something else. **R&D gives you information about what you should do next.** Stopping rule gives you principle for making optimal decision.

An **option** is a form of stopping rule: you buy the option to do X in the future at a price – for instance you buy the right to buy a stock at a specified future "strike price". If stock price rises you buy at given price and sell and make profit. If stock price falls you do not buy. The price of the option must be less than buying today. It allows you to buy or not when you have more information.

R&D is an option in which you invest to learn if some product/process works better than what exists today. You win if the R&D pays off. You learn something even if R&D shows your new product/process fails. You know this approach does not work so you should try another.

In the stock market the price of option rises with the variability of stock. If stock price changes a lot, the option is more valuable because there is chance the price rises above the exercise price, so you make money exercising the option. This differs from effect of volatility on the value of a share, where the risk is that you will have to sell when the price is down.

Given two opportunities with the same mean return **and right to stop at some point**, you can earn more with a higher variance because you can stop when the return is at a high value; whereas a fixed investment with greater variance is worth less than a safe fixed investment because you have put your money down and have to live with falls in the price.

R&D as option: Can always make a decision that ends the project before it "completes". The cost of R&D will depend on uncertainty of knowledge and the difference between the cost of R&D and cost of production. If RD is cheap and cost of production is big, do your R&D and make sure the product/process works before investing in production. **Most firm R&D is D. Most firm R is applied R.** So pattern is: spend some on basic R to learn how best to do D, which is more costly, before going to production.

TABLE 1. Funds spent for business R&D performed in the United States, by type of R&D, source of funds, and size of company: 2014–15
(Millions of U.S. dollars)

Selected characteristic and company size	2014	2015
Domestic R&D performance	340,728	355,821
Type of R&D[a]		
Basic research	21,936	21,792
Applied research	53,415	56,472
Development	265,377	277,558
Paid for by the company[b]	282,570	296,677
Basic research	16,107	16,306
Applied research	39,012	44,344
Development	227,451	236,027
Paid for by others	58,158	59,144
Basic research	5,829	5,486
Applied research	14,403	12,128
Development	37,927 i	41,530
Source of funds		
Federal	26,554 i	26,990
Other[c]	31,604	32,154
Size of company (number of domestic employees)		

Because R&D is risky, firms prefer a **portfolio** of RD by projects or approaches within a project. The risk of a portfolio depends on the correlation between projects. To get lower risk you invest in projects that are negatively correlated. This lets you "guarantee" a given rate of return. But a **portfolio of conditional R&D projects with option characteristics has lower risk than a portfolio of unconditional projects.**

The option feature substitutes for diversification, so even without diversification an investment set up as an option has lower risk than an unconditional project. You reduce risk by the ability to stop the project if it does not look promising. This is diversification over time.

By one metric, firms do not diversify portfolios – NSF 2008 estimated that 92% of firms devote all of their R&D to one line of business and that 82% with R&D expenses derived all of their worldwide sales from one line of business. But the 8% of firms with diversified R&D spending across multiple lines of businesses invested big in R&D. Companies reporting more than one line of business accounted for $107 billion (33%) of the $328 billion worldwide R&D expense for U.S. businesses.

I. Mathematics of Sequential Search and stopping rules

Assume you know the distribution of outcomes, including the max benefit, but that you don't know where the max is located . You spend $$ searching. The optimum strategy is to determine a RESERVATION WAGE (RW), so that the first offer W > RW you accept.

This is SEQUENTIAL SAMPLING in which you compare the marginal costs of another search against **the expected marginal gain of that search –** the expected value of another search minus the best you have up to that time. The result is a stopping rule.

On average searching can get you close to the max quickly even if you do not use a stopping rule. The **expected** value of the maximum after n searches with a **uniform distribution** is **[n/(n+1)]M**

1 search expected to have 1/2 maximum so the marginal gain is (1/2-0)M = 1/2 M
2 searches expect to have 2/3rds max so the marginal gain is (2/3 -1/2) M = 1/6 M
3 searches expect to have 3/4ths max so the marginal gain is (3/4 -2/3) M = 1/12M

The marginal gain is [1/(n)(n+1)] M. Say the maximum is 30 and each search costs you 2.5. You balance the declining payoff from an extra search against the constant marginal cost. If you decide # searches to undertake at the outset **-- fixed sample design** – you would calculating the **expected marginal gai**n:
1 -- 15 = 1/2 30
2 -- 5 = 1/6 30
3 -- 2.5 = 1/12 30. So you search three times.

But why keep searching if you hit the max on the first shot? Or stop at 3 if you got 1,2, 3 on the first draws. You know the distribution goes to M. Better is to undertake sequential search, which takes account of the information from the search itself to decide when to stop.

Arithmetic of the uniform distribution shows that the Reservation Wage in this case is 19: At 18 the **chance** of getting a higher value is 12/30 = 2/5. The extra varies from 1 to 12 to average 78 /12 or 6.5. Expected value is chance of higher 2/5 x expected average of 6.5 = 2.6, so the expected value from the search exceeds the cost. At 19 the chance of getting a higher value is 11/30. The amount extra varies from 1 to 11 for an average of 66/30 or 2.2, which is less than the cost. So your reservation wage would be 19.

But for basic R&D projects no one knows the maximum/distribution. So what we can do? **If you don't know the distribution, determine a DISCOVERY PHASE, then pick first project > MAX IN DISCOVERY. This is known as the Secretary Problem.** It is the reservation wage with less information.

You want the research project with highest payoff. You have a list of projects but **do not know** the distribution of payoffs. You take on a project or reject it on the spot.[1] You cannot turn down the project and then go back and undertake it. How can you maximize the probability of getting the best project?

The optimal strategy divides search into two stages: a discovery stage where you use information to select the reservation wage and a decision stage where you choose first project with value greater than reservation wage.

1Universities sometimes make "exploding offers": take my offer now or I withdraw it tomorrow when they want a candidate whom they fear will take MIT/H/P etc's offer over theirs. When do you accept the exploding offer?

With information on # of projects, the solution takes the first 1/e (~ 37%) observed projects as discovery, then pick the first next one that exceeds the reservation project. The probability this is the best is 1/ e as N–> infinite. With smaller numbers you do better.

Consider Three Projects ranked 1,2,3, where 1 is best. They can appear in any order: 1 2 3 1 3 2 2 1 3 2 3 1 3 1 2 3 2 1 If you randomly choose first, 2nd or 3rd you have 1/3rd chance of getting best. But if you use the first as a "base" and pick the next one with a better score, you get the best half the time. You improve your chances of getting the best project by 1/2-1/3 =1/6 – a 16% higher chance of getting best than random selection.

Why? If the best comes first 1,2,3 or 1,3,2 or last 3,2,1 you lose; but if you get **2,1,3 or 2,3,1 or 3,1,2 you win. This means win in ½ the time.** The gain is that 1 is first 2 times (1/3rd) but is 2nd 2 times and is 3rd in the 2,3,1 case. The extra bump occurs when you get a 2nd choice value first, and reject until you get 1.

Four Projects: 1/4th of cases you will get the top by chance, so we want to beat 1/4th

1 2 3 4	1 2 4 3	1 3 2 4	1 3 4 2	1 4 2 3	1 4 3 2	You lose
2 1 3 4	**2 1 4 3**	**2 3 1 4**	**2 3 4 1**	**2 4 1 3**	**2 4 3 1**	You win
3 1 2 4	**3 1 4 2**	3 2 1 4	3 2 4 1	3 4 1 2	**3 4 2 1**	you win on 3124 and 3142, 3412
4 1 2 3	**4 1 3 2**	4 2 1 3	4 2 3 1	4 3 1 2	4 3 2 1	you win on 4123, 4132

So you win on 11/24 giving a probability of success of 0.458.

Key question is how **many observations go into discovery phase?** Would you do better to let first two pass and then picking first > max of those 2? What if you had choice of 100 observations?

The solution is to calculate the probability of winning if you make R the cutoff point in discovery: you look at 1 …. R, then pick the first project after R with value > Max (1 … R). You lose if best project is among the first R, or if best is not among the first R but is preceded by project with lower value than the best at R+1 ....

Add up the probabilities, maximize wrt R so the cutoff point maximizes chance of getting the highest value among the R (1...R) cases. The R that maximizes chance of getting the highest value is the reservation wage.

Consider 10 candidates. Let's see how R=3 works, so the max you got from 3 searches is the reservation wage.

Fourth Observation: 1/10th chance that the fourth candidate is highest value

Fifth: 1/10th chance x chance that 4th one ≤ first three: 3/4 so this is 1/10 x 3/4

Sixth: 1/10th chance x chance that fifth one ≤ than first five: 3/5 so 1/10 x 3/5

nth: 1/10th chance x chance that the nth one ≤ than first n-1th

The sum of these probabilities (the chance you get the highest values at observation 4, 5, 6, …) gives the chance of getting the highest value for R= 3. Do the same for R=4 … 5 .. and on.

The Probability of Winning at

R+1: 1/n because there is a 1/n chance that at R+1st you get the max

R+ 2: 1/n, conditional that highest score up to R+1 is not R+1st. That probability is R/(R+1), so the probability of winning is (1/ n(R/R+1)).

R+3: 1/n (R/R+2) ... nth: 1/n (R/n-1) because all preceding (n-1) must have lower value and top is in R

This has solution that R = **1/e percent of universe – about 37% of the number of possible candidates – pick your reservation wage as the best in that set and then go with the first one that exceeds the best.** The chance you get the highest value using the rule is 1/n + R*/n [ln (n-1) - ln R*] ~ R*/n (Ln n/R*) = 1/e ln e = 1/e. For the math Havil Gamma: Exploring Euler's Constant shows how harmonic series and Euler's Gamma function → 1/e.

(Seale, D. A., & Rapoport, A. (2000). Optimal stopping behavior with relative ranks: The secretary problem with unknown population size. Journal of Behavioral Decision Making, 13, 391–411 – how to deal with ?? population)

The two step solution applies to problems with any sequence of random variables (stock prices, offers on a house, patient needs for a transplant) to maximize the reward **with no other information.** F. Thomas Bruss has written extensively on this as "ODDS-ALGORITHM" stopping rule. Sum the Odds to One and Stop The Annals of Probability Vol. 28, No. 3 (Jul., 2000), pp. 1384-1391

Exemplar problem: Throw die 12 times. Must declare "this is last 4" to win (comparable to selling used cars/house where you have offer and wonder if higher one will be down the pike). If the first throw is 4 should you take it? What is probability get another 4 in 11 chances? Should you wait until 12 throw in hope it is a 4?

ODDS-ALGORITHM is based on the odds ratio $\mathbf{r_k = p_k / q_k}$, where probability is p_k and $q_k = 1 - p_k$. The two step solution applies to problems with any sequence of random variables (stock prices, offers on a house, patient needs for a transplant) to maximize the reward **with no other information.** .

THE ALGORITHM: Sum the odds in reverse order $Rs = r_n + r_{n-1} + r_{n-2} + \ldots$ until this sum reaches or exceeds 1. If this happens at *s*, s is the stopping threshold and the rule is to pick the first 4 that comes up in the throws from s+1 on and declare it to be the last 4. The product Qk of chance that event did not occur $q_k = 1 - p_k$,

With $r_k = 1/5$ you have at period	12	11	10	9	8	7	**6**	
p_k	1/6	1/6	1/6	1/6	1/6			
q_k	5/6	5/6	5/6	5/6	5/6			
r_k	1/5	1/5	1/5	1/5	1/5			
so the sum Rs is	1/5	2/5	3/5	4/5	1			pick first 4 that occurs from 9 to 12
Product Qk =	5/6	$(5/6)^2$	$(5/6)^3$	$(5/6)^4$	$(5/6)^5$			

Then the odds algorithm/strategy maximizes the probability of stopping on the winning value with a probability of winning of QsRs.. In the dice case this is $(5/6)^5 = 0.402$

Theorem says: If $Rs \geq 1$, the win probability of stopping on the winning probability $\geq 1/e = 0.378$

Example 2: Accepting a job. What is the chance that any given offer is the highest THUS FAR? If you have k offers, chance that **any given offer** is highest will be 1/k – ie if you have two offers ½ chance first or second is highest; if you have three it is 1/3rd, etc. Now apply the theorem. Say you have 7 potential offers $r_k = p_k/q_k$ which varies with p**.**

Period	7	6	5	4	3
p_s	1/7	1/6	1/5	¼	1/3
r_n	1/6	1/5	1/4	1/3	½
Rn	1/6	11/30	37/60	171/180	261/180

So pick the best offer from 5th offer on ie 5, 6, or 7. $Q_3 = (2/3)(3/4)(4/5)(5/6)(6/7) = 2/7 = 0.286 \times 261/180 = 41\%$

Odds-algorithm
Write p_k, q_k and r_k in three lines and write each line i reverse order, that is, beginning with k = n:

(i) $p_n, p_{n-1}, p_{n-2}, \cdots$
(ii) $q_n, q_{n-1}, q_{n-2}, \cdots$
(iii) $r_n, r_{n-1}, r_{n-2}, \cdots$

Each r_k is the quotient of the numbers above it. No we sum up the odds in line (iii) until the value 1 reached or just exceeded. This yields the sum R_s = + r_{n-1} + ... + $r_s \geq 1$ with a stopping index s (if the su of odds never reaches 1 then we set s = 1). Then w compute from (ii) the product $Q_s = q_n q_{n-1} \cdots q_s$. This

Optimal strategy and win probability. The optimal strategy is to stop from s onwards on the first opportunity (if any).
The optimal win probability W is the product of R_s and Q_s, that is

$$W = R_s Q_s.$$

Note that the odds-algorithm gives us the optimal strategy and optimal value at the same time. Moreover, in the general case no other method could possibly do this more quickly, that is, the algorithm is optimal itself

THE ODDS THEOREM:

1) The odds-strategy maximizes the probability of stopping on the winning value.
2) The win probability of the odds-strategy equals $w = Q_s R_s$
   where $R_s = r_n + r_{n-1} + r_{n-2} + \cdots + r_s.$ and $Q_s = q_n q_{n-1} \cdots q_s.$
3) If $R_s \geq 1$, the win probability w is a≥ $1/e = 0.378\ldots$, which is best possible

If probability of success unknown, estimate using sequential updating F. Thomas Bruss and G Louchard The odds algorithm based on sequential updating and its performance Adv. in Appl. Probab. Vol 41, No 1 (2009), 131-153.

Squared Root of n minus 1 A variant on Prisoner's Dilemma (Bearden, "Comment: A new secretary problem with rank-based selection and cardinal payoffs"Journal of Mathematical Psychology 50 (2006) 58–591)

the payoff: Instead of the goal being to find the maximum, the payoff is equal to the selected applicant's underlying "true" value. Makes more sense that utility is higher closer to the max than has jump from 0 to 1.

the assumed distribution: calculation assumes uniform (but expect similar for other distributions).

You select exactly one applicant, cannot recall released applicants, and receives a payoff of xt, the realization of Xt, for selecting the tth applicant.

The algorithm. Estimate how many people you could see **n**; calculate **√n-1** as your discovery set; select first with value > discovery set max. Proven by calculating expected return to a given cutoff period and maximizing the expected return. Simple algebra with uniform.

"it seems unlikely that utility for selling at some prices slightly below the maximum would be zero. Compared to the classical secretary problem, it seems to us that the payoff scheme presented here is more natural."

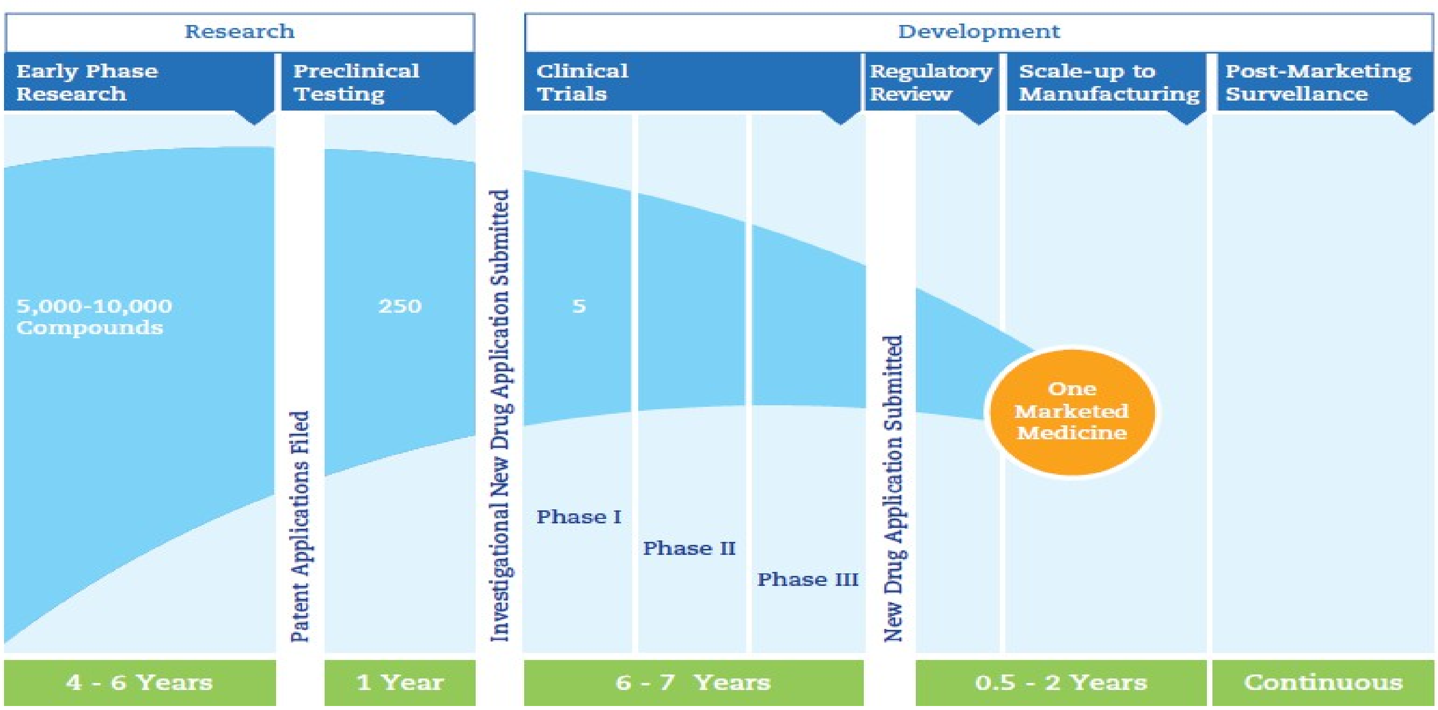
Difference between rules is that √n-1 has **smaller discovery period: if n =101, discovery period is 10 compared to 37.** But there are theorems that 1/e rule on average gets you high value in any case.

What people actually do: Use shorter discovery time than 1/e. We consider ... sequential observation and selection decision problems in which applicants are interviewed one at a time, decision makers only learn the applicant's quality relative to the applicants that have been interviewed and rejected, only a single applicant is selected, and payoffs increase in the absolute quality of the selected applicant. Compared to the optimal decision policy, results from two experiments show that **subjects terminated their search too early …** subjects tend to overestimate the quality of early applicants and give insufficient consideration to the yet-to-be-seen applicants. J. Neil Bearden, Amnon Rapoport, Ryan O. Murphy, (2006) Sequential Observation and Selection with Rank-Dependent Payoffs: An Experimental Study. Management Science 52(9):1437-1449. Several similar by team "Behavioral Decision-making Volume 19, Issue 3 July 2006 Pages 229–250

II. Example of research in stages, with value viewed as option: Pharma

Top R&D spending and R&D to sales Pharma ~ 17% of sales vs 8% for electronics/equip.

Figure 1: The research and development process[4]



Problem of funding transformative/high risk science: One big hit may be worth many small failures, but in Pharma the cost of big hit has risen.

RESEARCH AND DEVELOPMENT (R&D)[1]

Average time to develop a drug = **10 to 15 years**

Percentage of drugs entering clinical trials resulting in an approved medicine = less than **12%**

DEVELOPMENT COSTS

Average cost to develop a drug (including the cost of failures):[2]

2000s–early 2010s = **$2.6 billion**

1990s–early 2000s = **$1.0 billion***

1980s = **$413 million**

1970s = **$179 million**

TABLE 4: R&D by Function, PhRMA Member Companies: 2014

(dollar figures in millions)

Function	Dollars	Share
Pre-Human/Pre-Clinical	$11,272.7	21.2%
Phase I	$4,722.0	8.9%
Phase II	$5,697.8	10.7%
Phase III	$15,264.4	28.7%
Approval	$2,717.7	5.1%
Phase IV	$8,827.0	16.6%
Uncategorized	$4,751.5	8.9%
TOTAL R&D	$53,253.2	100.0%

Note: All figures include company-financed R&D only. Total values may be affected by rounding.
Source: Pharmaceutical Research and Manufacturers of America, PhRMA Annual Membership Survey, 2016.

But BIG PHARMACEUTICAL COMPANIES ARE SPENDING FAR MORE ON MARKETING THAN RESEARCH Washington Post, Feb 11,2015

Prescription drugs are a massive market: Americans spent $329.2 billion on prescription drugs in 2013. That works out to about $1,000 per person in the U.S., as John Oliver pointed out in his show on Sunday night.

Oliver also mentioned that nine out of 10 big pharmaceutical companies spend more on marketing than on research. León Markovitz of Dadaviz found and graphed those figures from healthcare research firm GlobalData in the graphic below. The amounts spent on sales and marketing are shown in orange, while the amounts spent on research and development are in bl

The biggest spender, Johnson & Johnson, shelled out $17.5 billion on sales and marketing in 2013, compared with $8.2 billi for R&D. In the top 10, only Roche spent more on R&D than on sales and marketing.

Most of this marketing money is directed at the physicians who do the prescribing, rather than consumers. As Oliver pointe out, drug companies spent more than $3 billion a year marketing to consumers in the U.S. in 2012, but an estimated $24 billion marketing directly to health care professionals.

Oliver closed his segment with a hilarious spoof commercial that urges patients to ask their doctors how pharmaceutical marketing might be influencing them.

"Ask your doctor today if he's taking pharmaceutical company money. Then ask your doctor what the money is for," the narrator says. "Ask your doctor if he's taken any money from the companies who make the drugs he just prescribed for you. Then ask yourself if you're satisfied with that answer."

What does sequential R&D decision get you: three variants of model

Early stage investment in R&D reduces dispersion of possible outcomes and changes the expected mean. To extent that R&D costs less than production, **"The value of R&D is almost all option value".** Discovery stage that reduces uncertainty in benefits or costs and then production stage modifies standard NPV calculation so that projects with NPV<0 can be worth doing to learn about the range of future outcomes.

Variant 1: The value of completed project is $5.00. Project requires a first phase RD investment of $2. You learn either a great solution that allows you to complete work for $0.00 or that completion will cost $6.10 with prob of ½. **Standard PV says DO NOT PROCEED.** Cost is $2+ ½ (0) + ½ (6.10) = $5.05, which exceeds $5.

But the sequential sample two stage decision SAYS DO STAGE ONE and then DECIDE to proceed or not. Cost for good result is $2.00. You proceed to costless second stage and earn $5

In bad result you spend the same $2.00 but do not proceed to the second phase and earn 0.

Your $2.00 got you a ½ chance of earning $5.00, which is worth the investment. RD stage one changed the nature of the investment from expected loss to return of $0.50 – 25% on your $2

Variant 2: Project costs $3.00 to complete but uncertain sales. Mean estimate of sales is $3.00 but there is ½ chance you will get a good shock of $3 and make $6 and a ½ chance you will get a bad shock of -3 and get $0.

Present value for full investment says don't do it. Cost of $3.00 and expected return of $3.00.

But in two stages with RD that **raises the cost but reduces the uncertainty of the sales, investment could pay off.** Assume RD costs $1 and tells you with certainty if you will get the bad or good sales shock.

Cost is 1.00 + 3.00 if learn that you will get positive kick and then earn $6.00

Cost is 1.00 if find out will get negative kick, in which case you do not proceed with project

So first period $1.00 gives you 1/2 (6.00-3.00) + 1/2 (0) = $1.50 in second period. A 50% expected return on the RD spending and overall return of .50 on your $4.00 or 12.5%.

This assumes R&D gave you exact answer but if it tells you are more *likely* to get positive kick, analysis goes through as well. VALUE OF KNOWLEDGE. Note if you decide not to proceed, it may look as if R&D costs were wasted but in fact the knowledge gained is worth it. FAILURE IS A SIGN OF SUCCESS.

Black-Scholes evaluation of option has explicit formula under assumption of normally distributed errors. Since R&D phases of R&D have compound options with non-normal errors, simulations to make optimal decision.

Variant 3: You have some returns in stage 1 but learn what to do in stage 2.

NPV for fixed sample is negative. But 2-stage sequential says proceed in stage one because you gain information about stage two. R is a random variable return which **can only be collected if both** phases are completed.

$R = R_1 + R_2$, where the random variable R_1 is revealed after stage 1 and R_2 is revealed after stage 2.

R_1 has an expected value(mean) of R_1 with a probability ½ of $+\sigma 1$ and probability ½ of $-\sigma 1$.

R_2 has an expected value(mean) of R_2 with a probability ½ of $+\sigma 2$ and probability ½ of $-\sigma 2$.

Phase 1 variation is larger: $\sigma 1 > \sigma 2$. The total return has ER_1+ER_2 with variance of $\sigma 1^2 + \sigma 2^2$; Costs are K1 in first stage and K2 in second stage.
Decision as "fixed sample" invest only if $E[R] = R_1 + R_2 > K1 + K2$.
Decision as two stage sequential decision process, proceed even if NPV is negative.

Why? Option of proceeding in stage one if you got positive result $+\sigma 1$ and stop otherwise makes NPV positive. With option, it is best to pay K1 and proceed. If get $R1 + \sigma 1$ continue. If get $R1 - \sigma 1$, stop. It will be optimal to undertake this at costs of -K1 -K2 if: Chance of good R2 outcome: $1/2(R1 + R2 + \sigma 1 + \sigma 2)$ + chance of bad R2 outcome: $1/2 (R1 + R2 + \sigma 1 - \sigma 2) > 0$ --- ie if $R1 + R2 + \sigma 1 > K1 + K2$.

Thus, bigger $\sigma 1 \rightarrow$ more likely we want to proceed. RISK (symmetric) IS GOOD. It measures how much information is obtained about the ultimate value of R after one stage of R&D. If information is obtained cheaply ($\sigma 1$- K1 is large), do the project.

III.Portfolio and diversification

"I puts it all away, some here, some there, none too much anywheres, by reason of suspicion" Captain Long John Silver, chapter 11 Treasure Island

Diversification reduces the variability of returns around the expected return. The goal is to diversify so that no other asset or portfolio of assets has higher expected return with the same/lower risk, or lower risk with the same/ higher expected return. With n projects,with expected returns of E(Ri) and wi as proportions of total investment in each project, $E(Rp) = \Sigma wi\, E(Ri)$ and variance of portfolio is weighted sum of variances and covariances

$$\sigma_p^2 = \sum_i w_i^2 \sigma_i^2 + \sum_i \sum_j w_i w_j \sigma_i \sigma_j \rho_{ij}$$

where ρ_{ij} is the correlation between i and j. Covariance is standard deviation of i multiplied by standard deviation of j x the correlation between I and j.

Combining securities that have perfect positive correlation does not reduce portfolio risk.
Combining securities with zero correlation reduces the portfolio risk, which goes to 0 as n → infinity.
Combining securities with perfect negative correlation can eliminate risk altogether.

Example: Asset A has E(R) 10% and σ_A of 20% while Asset B has E(R) of 16% and σ_B of 30%

Consider a portfolio of ½ A and ½ B. Since E is linear the return for the portfolio lies on a straight line between A and B – so it is 13%. Now $\sigma_P{}^2 = (1/2\ \sigma_A)^2 + (1/2\ \sigma_B)^2 + 2(1/2)(1/2)\ \sigma_A \sigma_B \rho_{AB} = ¼\,(0.20^2 + 0.30^2) + 2(¼)\ (.06)\ \rho_{AB} = ¼\,(.13) + .03\ \rho_{AB} = .0325 + .03\ \rho_{AB}$\ where ρ_{AB} is the correlation of the assets

Then if $\rho_{AB} = 1$, $\sigma_P{}^2 = 0.0625$ and $\sigma_P = 0.25$. Linear average of the SDs
if $\rho_{AB} = 0$, $\sigma_P{}^2 = .0325 =$ and $\sigma_P = 0.18$. A much lower standard deviation
if $\rho_{AB} = -1$, $\sigma_P{}^2 = .0325 - .03 = .0025$ and $\sigma_P = 0.05$, much smaller. Close to zero. When will the perfect negative correlation eliminate risk completely?

An option reduces risk since you can stop a project that looks bad in phase one. In a portfolio of options the option limits downside risk of the individual project. This makes project payoffs non-linear and the value distribution becomes skewed. If projects are positively correlated, convexity enhances diversification and overall risk becomes lower than under standard analysis. But if the projects are negatively correlated, portfolio risk is largely independent of diversification; when projects are positively correlated diversification is more effective than these tools predict. As a consequence, options are more complex instruments for diversification.

Principal Investigators do portfolio investment implicitly when they direct lab to undertake different projects. They assign different grad students or postdocs to different projects. Would expect larger labs to take greater risks. Firms also make decisions that reflects the option model but very few apply the formal math. Research-Technology Management, Sept-Oct 2007). :

4 What firms actually do.

Gino and Pisani, HBS, 2006): the complexity, ambiguity, and uncertainty of most companies' R&D portfolios make it impossible to optimize per the mathematical model; (Lockett and Gear, 1973).

"The decision-theoretic models proposed in the literature are themselves highly complex and, as a result, they have not become a tool that is commonly used in management practice" (Loch and Kavadias, 2002)

Bain and Co. 2000 survey found that only 9% out of 451 participants use ROA while observing an abandonment rate of 32%. Only Merck and Co. reported using real options pricing with B/S to value biotech investments (Nichols, 1994). Remer et al. (2001) report that European biotechnology companies know but do not apply real options **Hartman and Hasan Research Policy 2006** survey pharma firms to see what they use.

Table 1

Evaluation methods in the pharmaceutical section (E)NPV: (Expected) Net Present Value, DCF: Discounted Cash Flow, RoE: Return on Equity, RoI: Return on Investment, EVA®: Economic Value Added

	Valuation methods									Risk analysis and further criteria					
	NPV / ENPV / DCF	RoE / RoI / EVA®	Internal rate of return	Scoring model	**Real options analysis**	Net asset value	Capitalised earnings value	Multiples	Other	Monte Carlo simulation	Decision trees	Scenario analysis	Sensitivity analysis	Payback period	**Number of answers**
R&D stages															
Research	59%	6%	18%	47%		6%		6%	6%	6%	29%	29%	18%	18%	17
Pre-clinic	76%	12%	24%	24%	12%	4%			4%	20%	56%	60%	48%	16%	25
Clinical phase I	85%	15%	27%	19%	23%	4%			4%	19%	69%	69%	69%	23%	26
Clinical phase II	100%	19%	22%	11%	26%	7%			7%	26%	74%	67%	74%	26%	27
Clinical phase III	100%	22%	30%	11%	26%	7%		4%	11%	33%	74%	67%	78%	30%	27
Registration	96%	21%	29%	8%	21%	8%		4%	13%	38%	71%	67%	75%	29%	24
Company valuation															
Early biotech	82%	18%	9%			9%	9%	27%	9%		18%	9%	45%	36%	11
pYoung biotech	89%	11%	11%			11%	11%	22%	11%		22%	22%	56%	56%	9
Old biotech	80%	40%	20%			20%					40%	80%	60%	40%	5

The Radical Innovation Research Program sponsored by the Industrial Research Institute's Research-on-Research committee. Phase 1, from 1995–2000, examined 12 RI projects in ten large companies: Air Products and Chemicals, Analog Devices, DuPont, GE, GM, IBM, Nortel Networks, Polaroid, Texas Instruments, and United Technologies. This phase determined that RI project teams could be better managed if companies took a more systematic and systems oriented approach.

"Phase II from 2001–2005, compared 12 companies that had a declared strategic intent to develop or evolve their RI capability... analyzing top-management-driven systems-level approaches. We observed that a number of grass roots approaches to developing continuing capability in breakthrough innovation for corporate growth and renewal had taken root but had not thrived." … companies involved in this second longitudinal study were 3M, Air Products and Chemicals, Albany International, Corning, Dupont, GE, IBM, J&J Consumer Products, Kodak, Mead Westvaco, Sealed Air and Shell Chemicals. An additional nine companies (Bose, Dow Corning, Guidant, HP, Intel, P&G, PPG, Rohm & Haas, Xerox) served as our validation set and could be characterized as Phase III of the program. (Paulson, et al Research-Technology Management, Sept-Oct 2007). Here are sections in this tool:

		Response	
VIII	**Portfolio Health**	Portfolio	
		Relevance (0, 1)	Value Level (1-5)
8.1	Overall, the company has an adequate number of major innovation projects in its portfolio.	1	2
8.2	The portfolio of projects is well-diversified with respect to ultimate market domains.	1	4
8.3	Each of the projects in the portfolio constitutes a significant portion of a balanced portfolio of investments, given each project's stage of maturity across Discovery, Incubation and Acceleration.	1	4
8.4	We have not spread our resources too thin across too many projects in this portfolio.	1	4
8.5	The projects in this portfolio represent the strategic intent of this firm in terms of business domains and technical competencies we want to dominate in the future.	1	5
8.6	The projects in this portfolio are benefiting from synergistic effects on one another.	1	5
8.7	The portfolio of projects can be framed so as to enjoy patent protection and competition blocks.	1	3
8.8	Our major innovation projects form the basis of a continuing pipeline of potential significant commercializations.	1	4
8.9	The 'churn rate' of projects in the portfolio that are in the discovery phase is appropriate.	1	5
8.10	The 'churn rate' of projects in the portfolio that are in the incubation phase is appropriate.	1	5
8.12	Our portfolio of projects is sufficiently diverse in terms of new capabilities that we are trying to develop.	1	5
8.13	The estimated time to commercialization of the projects in the portfolio is well balanced.	1	3
	Total Value		**49**
	Maximum Potential Value		**60**
		% of Drivers Important	% of Max Value
	Portfolio totals	**100.0**	**81.7**

IV	**Project's Impact on the Portfolio:** *The extent to which the project helps bring the portfolio to a healthy balance on any of our desired dimensions for portfolio diversification.*	PSTC Project S		PSTC Project D		
		Relevance (0, 1)	Value Level (1-5)	Relevance (0, 1)	Value Level (1-5)	Releva (0,
4.1	There are possibilities for synergistic effects between this project and others in the portfolio.	1	5	1	5	
4.2	This project is unique enough that it will not cannibalize any other project in the portfolio.	1	1	1	1	
4.3	If this project were killed, the portfolio would suffer.	1	5	1	5	
4.4	This project provides balance to the portfolio of major innovations in terms of pacing of projects. It helps balance the portfolio in terms of number of projects in discovery, incubation and acceleration phases.	1	3	1	3	
4.5	This project is providing balance to the portfolio of major innovations in terms of desired risk in the portfolio.	1	5	1	5	
4.6	This project is providing balance to the portfolio of major innovations in terms of technology domains we're invested in.	1	5	1	5	
4.7	This project is providing balance to the portfolio of major innovations in terms of business domains we're invested in.	1	5	1	5	
	Total Value		**29**		**29**	
	Maximum Potential Value		**35**		**35**	
		% of Drivers Important	% of Max Value	% of Drivers Important	% of Max Value	% of Dr Impor
	Project totals	**100.0**	**82.9**	**100.0**	**82.9**	**#DIV**

3.Adjustment costs of RD and cyclical sensitivity

R&D varies with cycle but less so than physical capital investment. For instance, between 2008 and 2009 real investment in the GDP accounts fell by 21% while RD fell by 0.4%. Indicative of the stability of R&D at the firm level, firm R&D growth is more highly related to past R&D growth than sales, employment or investment: growth rates correlated with growth rates 2 years earlier: R&D (0.69), investment (.274), employment (.095), sales (.082).

Given that most of business R&D is D, which is closer to I than to basic research, also valuable to compare business spending on basic, applied, and development over cycle.

Most analysis focuses on fact that R&D is cyclical (Barlevy, AER, Sept 2007) because "inter-temporal substitution" models predict that firms should do R&D and training/education in recessions when the value of production is lower. But the same argument could be made for physical investment! Invest in the middle of recession so you are ready to produce in the coming boom.

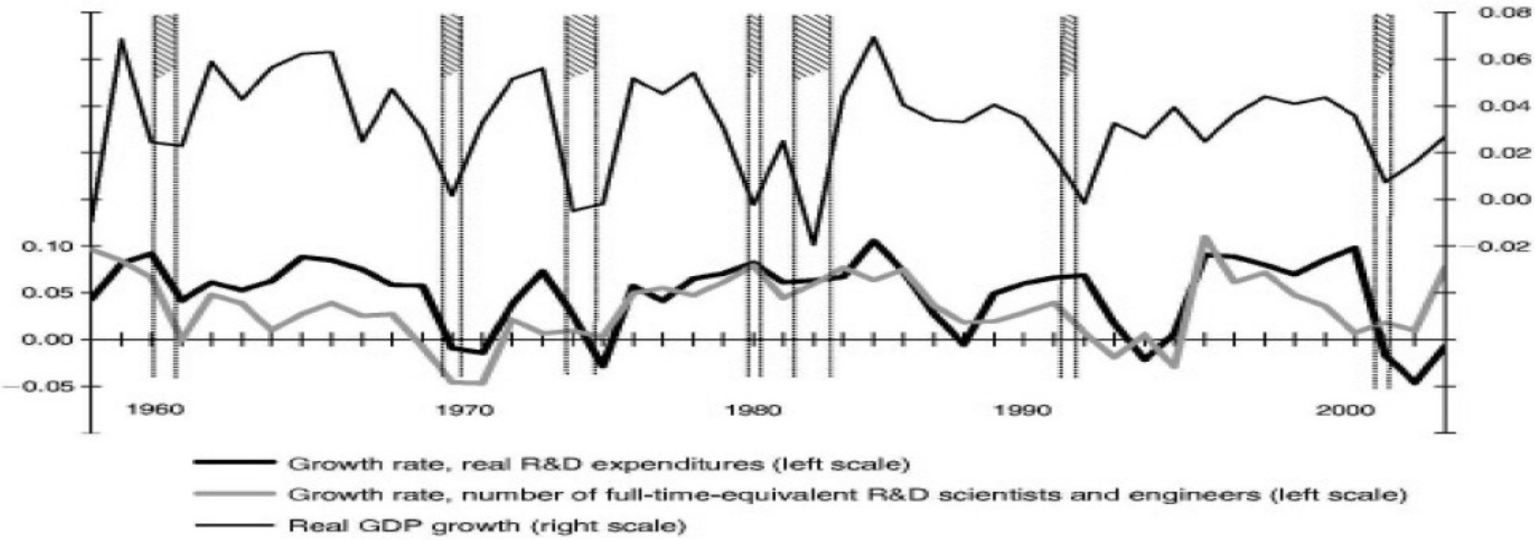


FIGURE 1. MEASURES OF R&D OVER THE BUSINESS CYCLE

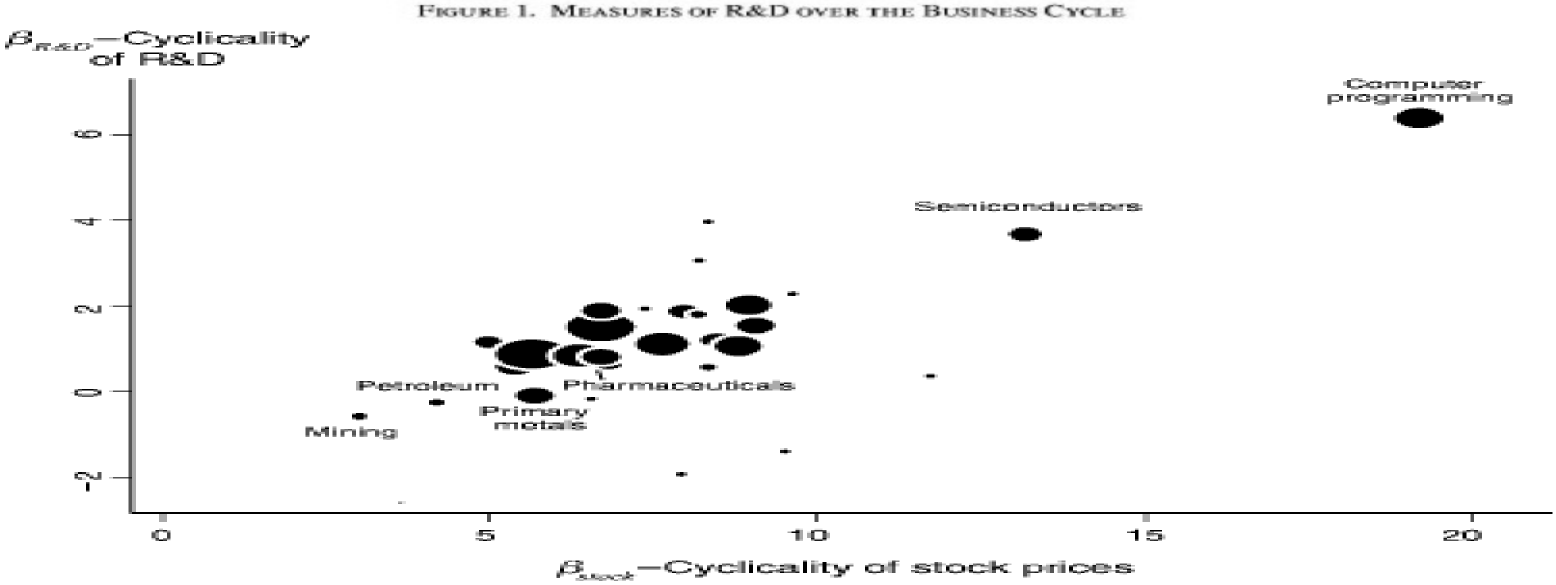


FIGURE 3. CYCLICALITY OF STOCK PRICES (β_{stock}) AND R&D ($\beta_{R\&D}$) ACROSS INDUSTRIES
(Observations weighted by the standard error of the estimate of R&D cyclicality in each indu

Why is RD cyclical instead of counter-cyclical?

1- Cash flow and budgetary problems in the cycle? Not enough to explain because firms more likely to maintain RD than I and shift money to keep RD going.

2- RD labor is specialized and difficult to substitute over time so the substitution over time is very weak effect

3- Firms ignore "dynamic externality" that says better to do RD now so others can use it and benefit firm/economy. Entrepreneurs concerned with short-time benefits … do RD in boom to catch higher profits

4- IGNORES what booms/busts do to expectations (because RE takes care of such problems)

SIDEPOINT OF SOME IMPORTANCE: While business R&D varies with the cycle it is not the main cause of fluctuations in the research market. The main cause is the government. From 1953 to 2007 government RD/GDP showed virtually no trend. It was 0.73 in 1953 and 0.71 in 2007. But it varied massively as the following indicates.

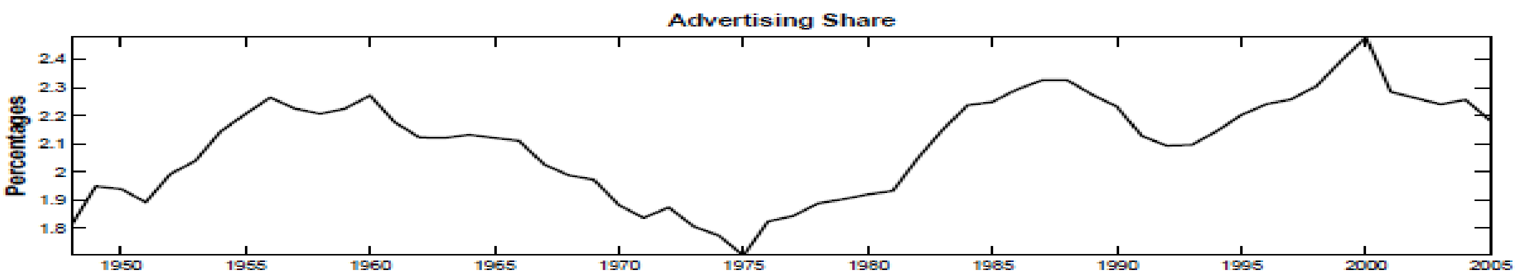
	Gov RD/GDP	Nonfederal RD /GDP
1953	0.73	0.63
1964	1.92	0.96
1978	1.06	1.06
1985	1.25	1.47
2000	0.68	2.05
2007	0.71	1.95

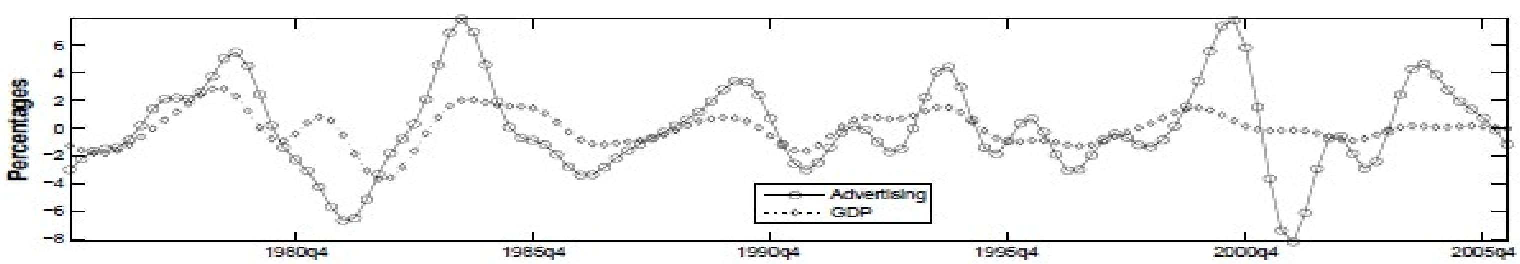
Then ARRA with rise in Govt RD/GDP

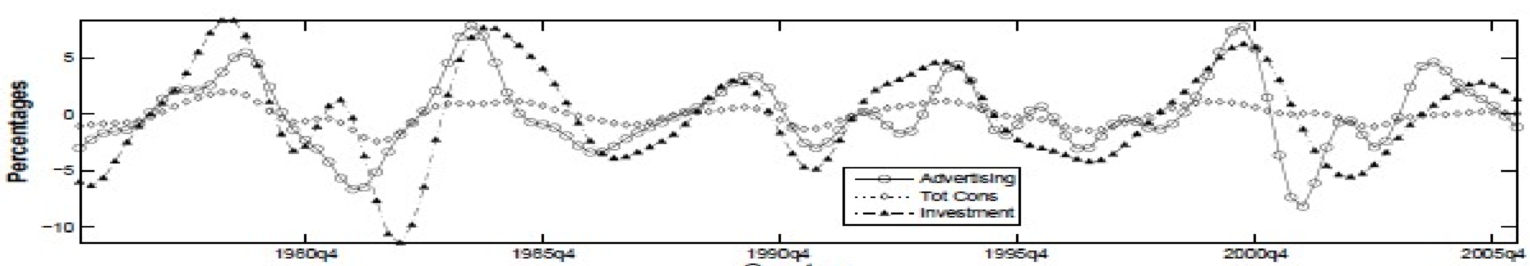
Biggest annual changes: Govt 0.24, 0.21, -0.11, -0.12; Non-federal: 0.16, 0.09, 0.13 -0.12

An alternative question is **why is R&D is LESS cyclically sensitive than physical investment?** Investment in intangibles may be more stable and less sensitive than investment in tangible assets.

Consider another intangible … advertising. To the extent that advertising has a high rate of obsolescence, it ought to be more cyclical than R&D. Here is some data that shows advertising is less stable and shows greater variability than GDP (so its share is cyclical) but much less than investment and more than RD:







The idea is that the adjustment cost of changing an input has two parts:

When you change a capital stock there is a cost to the change – for physical capital that is the primary cost since you "buy the Investment goods in the market": Cost = a Δ K = a I. When you change the stock of knowledge, knowledge is intangible that you do not buy or sell it. The cost of adjustment is in the flow of RD = b Δ RD since the main cost is hiring scientists and engineers, setting up your project activity etc,not in using the ideas – they become part of the cost of production but not the RD activity. It is more expensive to change RD when the world changes because it involves more than canceling an order for a new machine. So RD has greater persistence.

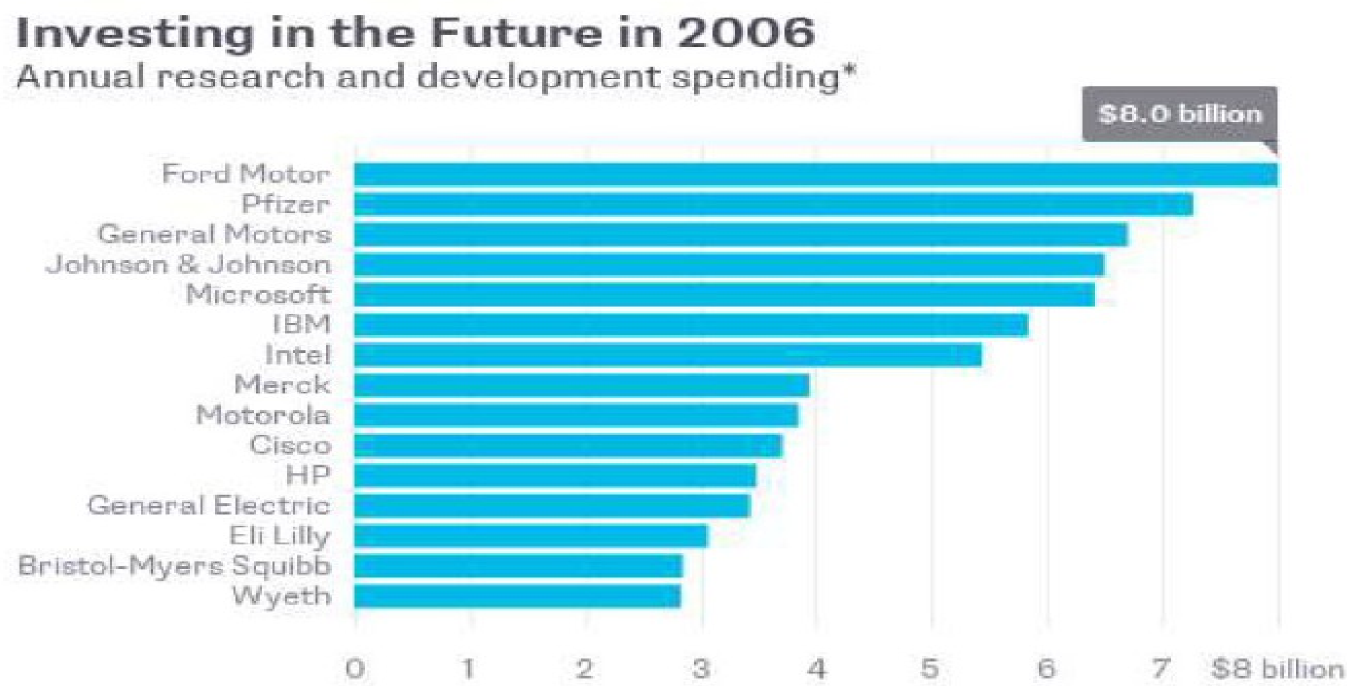
How Particular Firms Rate in R&D

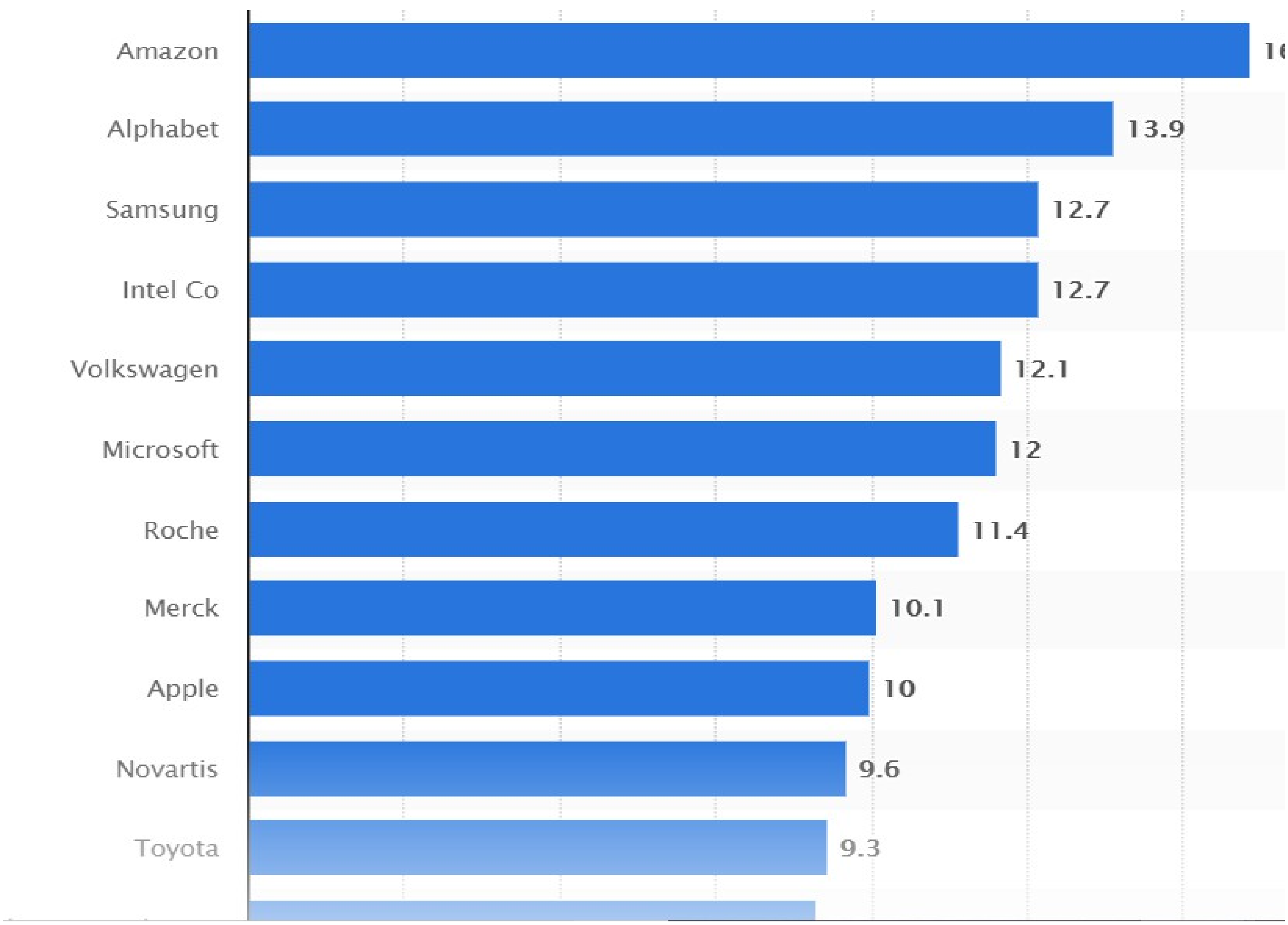
Strategy, PwC's strategy consulting business, identified the 1,000 public companies around the world that spent the most on R&D during fiscal year June 30, 2017. Companies had to make their R&D spending numbers public. Subsidiaries more than 50 percent owned by a single corporate parent during the period were excluded if their financial results were included in the parent company's financials. The Global Innovation 1000 collectively account for 40 percent of the world's R&D spending, from all sources, including corporate and government sources.

In prior years, both capitalized and amortized R&D expenditures were excluded. Starting in 2013, we included the most recent fiscal year's amortization of capitalized R&D expenditures in calculating the total R&D investment, while continuing to exclude any non- amortized capitalized costs. We obtained from Bloomberg and Capital IQ the key financial metrics for 2012 through 2017, including sales, gross profit, operating profit, net profit, historical R&D expenditures, and market capitalization. All companies were coded into one of nine industry sectors (or "other") according to Capital IQ's industry designations, and into one of five regional designations, as determined by their reported headquarters locations. The R&D spending levels and financial performance metrics of each company were indexed against the average values in its own industry. Finally, to understand the ways in which global R&D is and will be conducted at companies across multiple industries, **Strategy& conducted an online survey of 562 innovation leaders around the world.**

				R&D Expenditures ($US Billions)	Revenue ($US Billions)	R&D Intensity
2017 Rank	Company Name	Country	Industry group	2017	2017	2017
1	Amazon.com, Inc.	United States	Retailing	16.1	136.0	11.8%
2	Alphabet Inc.	United States	Software and Services	13.9	90.3	15.5%
3	Intel Corporation	United States	Semiconductors and Semicon...	12.7	59.4	21.5%
4	Samsung Electronics Co., Ltd.	South Korea	Technology Hardware and Eq...	12.7	167.7	7.6%
5	Volkswagen Aktiengesellschaft	Germany	Automobiles and Components	12.1	229.4	5.3%
6	Microsoft Corporation	United States	Software and Services	12.0	85.3	14.1%
7	Roche Holding AG	Switzerland	Pharmaceuticals, Biotechnolo...	11.4	51.8	21.9%
8	Merck & Co., Inc.	United States	Pharmaceuticals, Biotechnolo...	10.1	39.8	25.4%
9	Apple Inc.	United States	Technology Hardware and Eq...	10.0	215.6	4.7%
10	Novartis AG	Switzerland	Pharmaceuticals, Biotechnolo...	9.6	49.4	19.4%
11	Toyota Motor Corporation	Japan	Automobiles and Components	9.3	247.5	3.8%
12	Johnson & Johnson	United States	Pharmaceuticals, Biotechnolo...	9.1	71.9	12.7%
13	General Motors Company	United States	Automobiles and Components	8.1	166.4	4.9%
14	Pfizer Inc.	United States	Pharmaceuticals, Biotechnolo...	7.9	52.8	14.9%
15	Ford Motor Company	United States	Automobiles and Components	7.3	151.8	4.8%
16	Daimler AG	Germany	Automobiles and Components	6.9	161.8	4.2%

Today's list of top R&D spenders different than past lists:





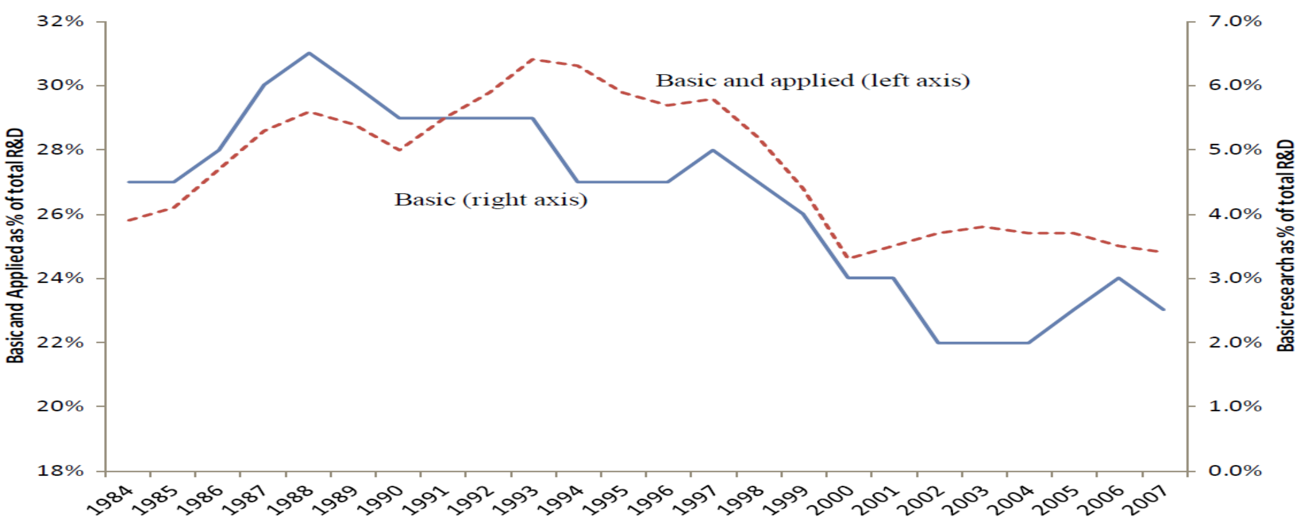
Decline of Corporate Basic R&D: aka death of Bell Labs, etc

Key papers: KILLING THE GOLDEN GOOSE? THE DECLINE OF SCIENCE IN CORPORATE R&D Ashish Arora Sharon Belenzon Andrea Patacconi NBER 20902; Back to Basics: Why do Firms Invest in Research? Ashish Arora, Sharon Belenzon, Lia Sheer NBER Working Paper No. 23187

Fu, etc (2015) "Why Do U.S. Firms Invest Less Over Time?" http://ink.library.smu.edu.sg/cgi/viewcontent.cgi?article=5245&context=lkcsb_research, Singapore Management University

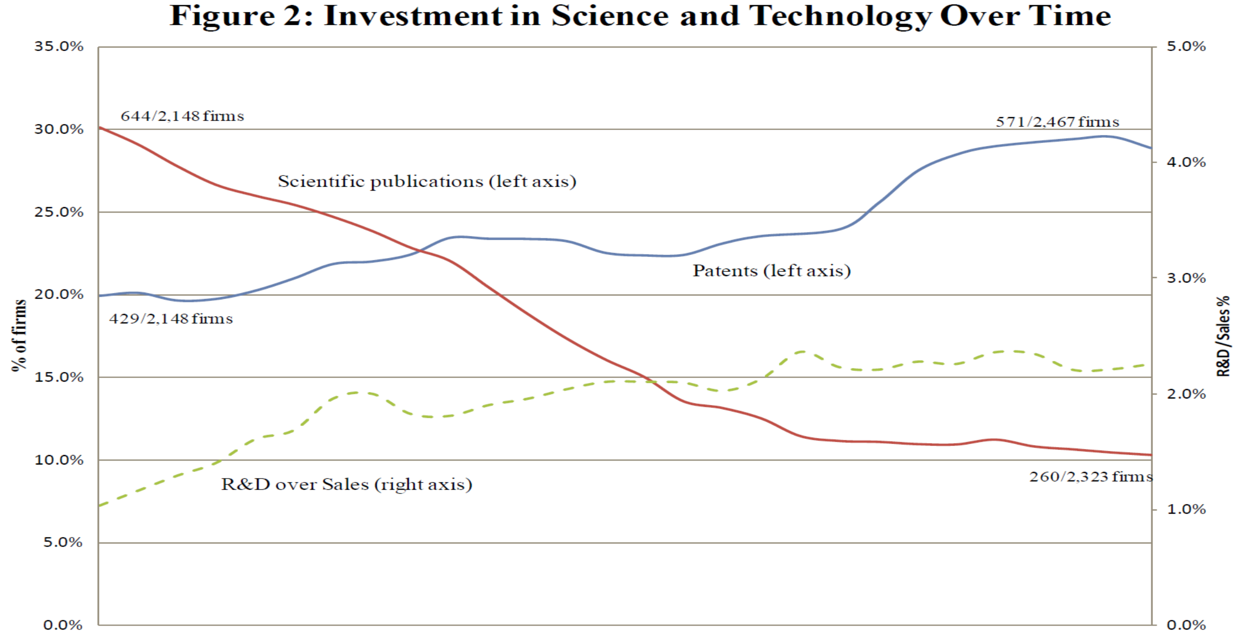
find capital expenditure of U.S. public firms declines substantially since 1980s. The decline is pervasive: it occurs in almost every industry and is not concentrated in firms with certain specific characteristics. The decline is not explained by new listing effects, corporate lifecycle, or time-variation of investment opportunities and financial constraint. The decline seems to be related to the transition of the U.S. economic structure and globalization. When an investment opportunity arises, firms in the early period respond with more investment in fixed assets while this sensitivity reduces much for firms in the recent decades. Recent firms focus more on developing intangible assets and human capital through, e.g., spending on R&D and SG&A.

Share of research in total non-Federal R&D



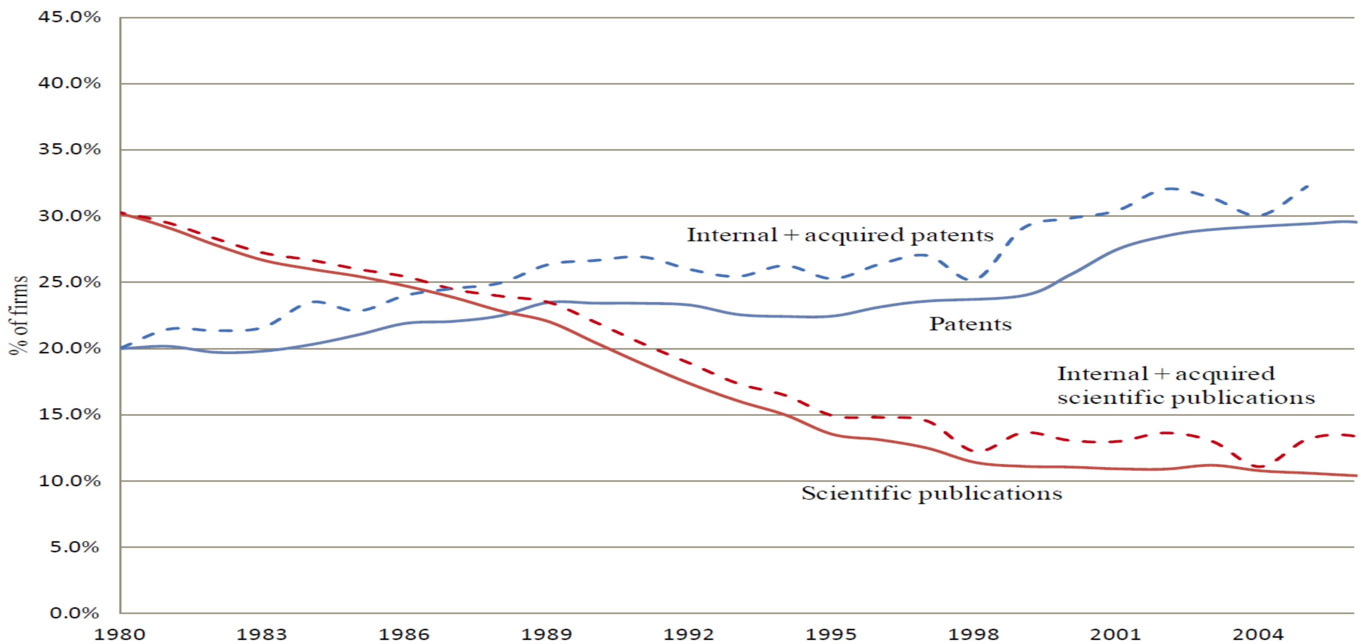
Data source: National Science Foundation/Division of Science Resources Statistics, Survey of

Figure 2: Investment in Science and Technology Over Time



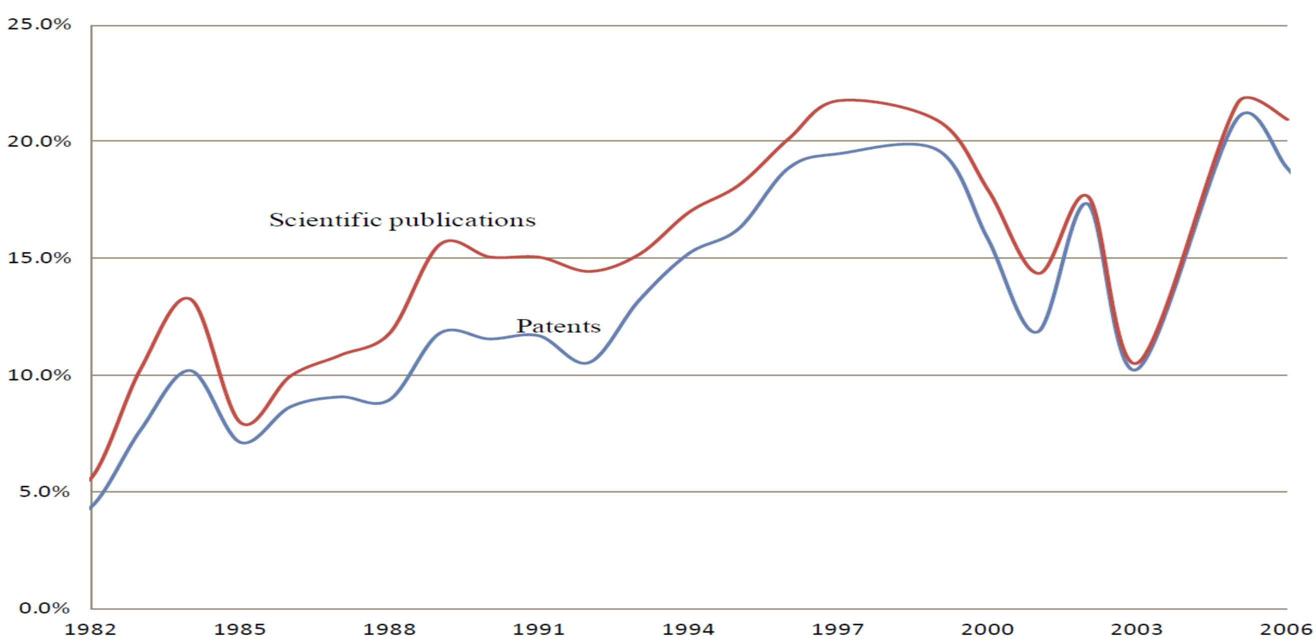
Note: This figure presents the share of publishing and patenting firms of all Compustat firms with at least one year with non-zero R&D expenditures, over time. Data source: Compustat, Web of Science, PatStat.

Figure 4: Combining Investment in Science and Technology and Sourcing Over Time



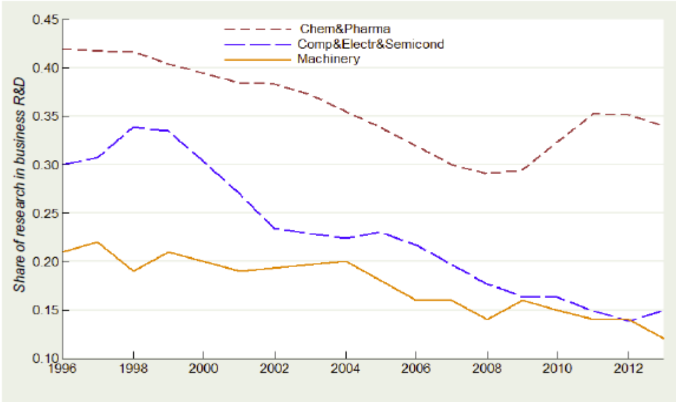
Note: This figure combines internal and acquired publications and patents. The dashed lines present the combined shares. Data source: Compustat, SDC Platinum, Web of Science, PatStat.

Figure 3: Sourcing of Science and Technology Over Time

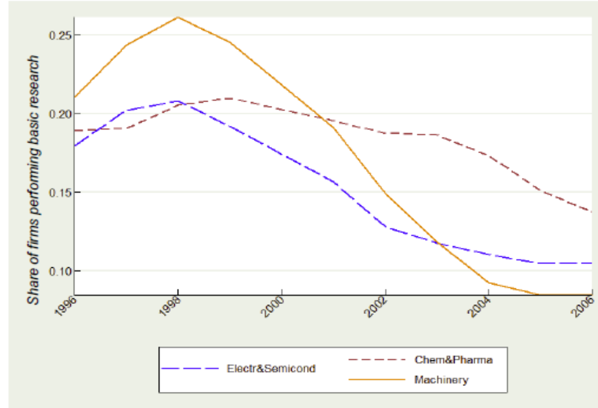


Note: This figure presents the share of publishing firm that acquire targets with scientific publications, and the share of patenting firms that acquire targets with patents, over time (3-year moving average). The dotted line plots the share of fir scientific articles that are coauthored with an external scientist. Data source: SDC Platinum, Web of Science, PatStat.

Share of basic and applied research by industry sector 1996-2013

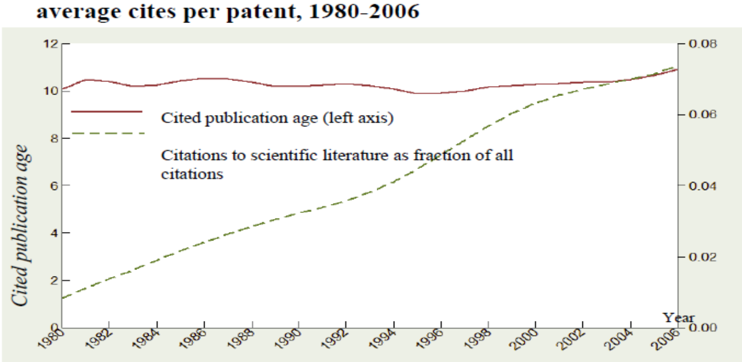


Share of companies performing basic research out of all R&D performers, 1996-2006



Finding: The decline in corporate research is broad-based, present in a range of industrial sectors

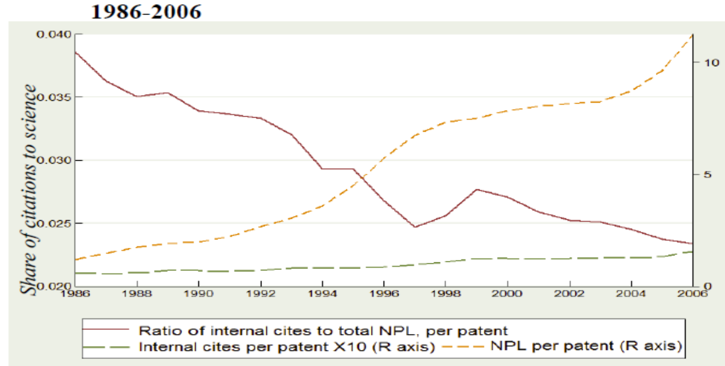
Average age of scientific publications cited in patents and average cites per patent, 1980-2006



Finding: Corporate patents cite science at higher rates over time; cited science is not older science

Implication: **R remain useful for D**

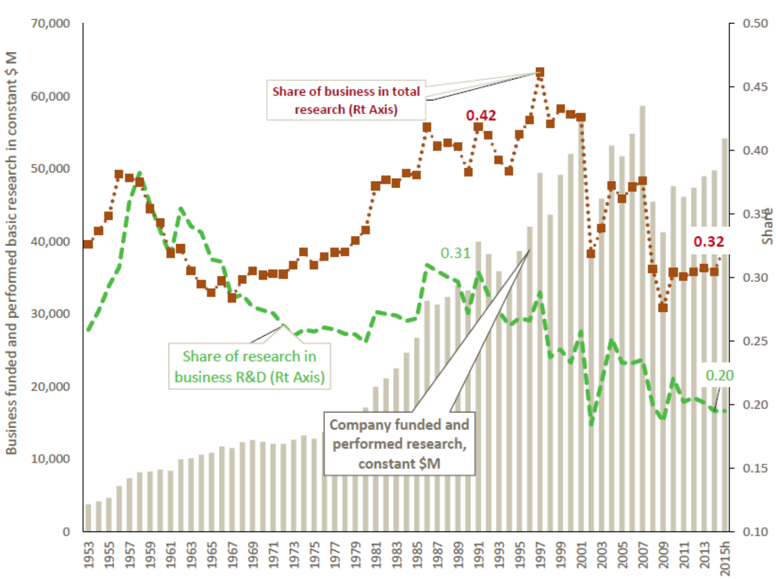
Cites to scientific publications by corporate patents, 1986-2006



Finding: Corporate patents cite external science at higher rates over time

Implication: **Firms rely on externally funded R for D, including federally funded R**

Business funded and performed research in the U.S., 1953-2015

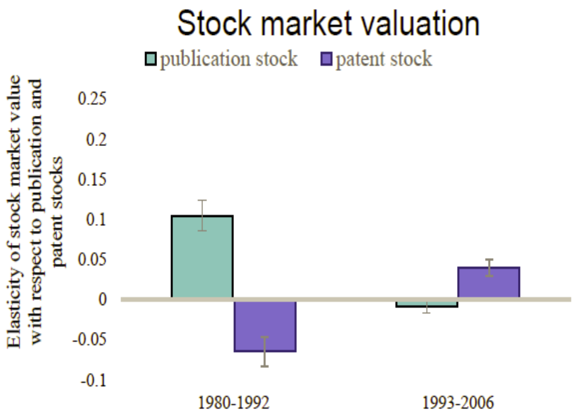


Findings: Firms investing less in research even as overall R&D increases

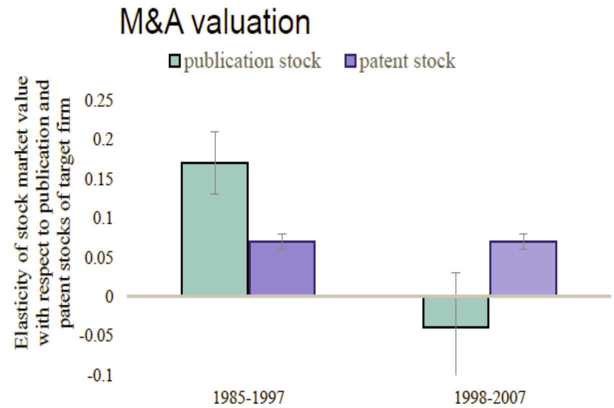
- Absolute spending below 1999 in real terms
- Share of business in U.S. research is 30%, down from 45% (1990s)
- Share of research in business research is 20%, down from 30% (1990s)

Implication: **Less "R", more "D"**

Decline in private value of research



Note: The estimates are from regressing stock market value against firm's assets, R&D stock, publications stock, patents stock, and a complete set of dummies for year and industry. The sample consists of firms with at least one patent and one publication. The sample period is 1980–2006.



Note: This figure presents estimates of elasticity of acquisition value with respect to publication and patent stocks by year cohorts for acquired firms. The estimates are from regressing stock market value against firm's assets, sales, publications stock, patents stock, and complete set of dummies for year, industry codes, target country and acquisition year. The sample includes all SDC Platinum deals with complete information on target firm value, assets, and sales. The sample period is 1985–2007.

Finding: The value of publications has dropped and the value of patents has increased over time for both investors and managers

Implication: Over time, firms and investors value "D" relative to "R"

Note this is not production function but stock market and M&A valuation. But likely consistent with production function evidence, per Are Ideas Getting Harder to Find? Nicholas Bloom, Charles I. Jones, John Van Reenen, Michael Webb NBER Working Paper No. 23782

Arora et al conclusion

Findings
- Corporations are withdrawing from research
- Startups will not fill the breach
- Research findings continue to be relevant for invention
- Corporations are using external research

Interpretation: A division of innovative labor
- Reallocation of research from large corporate labs to more efficient and specialized research organizations (e.g., universities)
- Established firms source inventions from universities, often through start-ups

Policy Implications
- Public funding for research is even more important for maintaining American competitiveness