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.

An **option** is a right to do something: you pay today for right to, say 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 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.

Since you learn as you do R&D we will treat it as a **sequential decision – you decide to begin an R&D investment project and when you find out more, either you continue or you stop.** 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.

R&D is a REAL 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.

Is this any different than advertising? You buy some ads telling consumers about your product and you learn whether the ads sold more product or not. If ads failed, stop the campaign.

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. By contrast, while volatility raises the value of an option but reduces the value of a share if people are risk averse. 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 paid the full cost of the investment and have to live with falls in the price.

R&D as option: Can always make a decision that ends the project. 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 entering production. **Most firm R&D is D. Most firm R is applied R.** Firms spend a bit on basic R to learn how best to do D, which is more costly, before going to production, which is even more expensive.

TABLE 12

Domestic R&D paid for by the company and others and performed by the company, by type of R&D, industry, and company size: 2017

(Millions of U.S. dollars)

Industry and company size	NAICS code	Total	Basic research	Applied research	Development
All industries	21–23, 31–33, 42–81	400,100	24,829	62,132	313,139
Manufacturing industries	31–33	257,227	18,624	43,698	194,904
Food	311	4,697 i	466 i	1,518 i	2,713
Beverage and tobacco products	312	1,076	142	257	677
Textile, apparel, and leather products	313–16	920	35	79	806
Wood products	321	175	11	39	125
Printing and related support activities	323	229	17	52	160
Chemicals	325	74,977	10,193	17,021	47,763
Pharmaceuticals and medicines	3254	66,202	9,362	14,890	41,950
Other chemicals	other 325	8,775	831	2,132	5,813
Plastics and rubber products	326	3,754	375	771	2,608
Nonmetallic mineral products	327	1,334	161 i	280 i	893 i
Primary metals	331	749	36	80	633
Fabricated metal products	332	2,206	187	347	1,672
Machinery	333	13,197	639	1,521	11,037
Computer and electronic products	334	78,575	2,543 i	11,194	64,837
Semiconductor and other electronic components	3344	30,148	923 i	4,720 i	24,506 i
Navigational, measuring, electromedical, and control instruments	3345	14,509	726 i	2,108	11,675
Other computer and electronic products	other 334	33,918	894	4,367	28,656
Electrical equipment, appliances, and components	335	4,291	300 i	708	3,284
Transportation equipment	336	53,292	2,824	7,490	42,978
Aerospace products and parts	3364	26,383	1,616 i	3,782	20,986
Other transportation equipment	other 336	26,908	1,208	3,708	21,992
Furniture and related products	337	422	32	77	313
Miscellaneous manufacturing	322, 324, 339	17,332	663	2,263	14,407
Nonmanufacturing industries	21–23, 42–81	142,874	6,205	18,434	118,235
Information	51	80,252	2,243	7,626	70,383
Publishing	511	34,338	1,095	2,702	30,542
Telecommunications	517	3,682 - 3,806	268	1,511	1,902 - 2,027
Data processing, hosting, and related services	518	16,155	687	2,004	13,464
Other information	other 51	25,954 - 26,077	194	1,408	24,351 - 24,476
Professional, scientific, and technical services	54	36,922	2,491	8,584	25,848
Architectural, engineering, and related services	5413	2,708	260	968	1,479
Computer systems design and related services	5415	13,327	898	2,243	10,185
Scientific research and development services	5417	17,321	1,178	4,814	11,329
Biotechnology research and development	541711	4,449	515	253	3,680
Physical, engineering, and life sciences (except biotechnology) research and development	541712	11,913	594	3,943	7,377
Social sciences and humanities research and development	541720	959	70 i	618 i	271 i
Other professional, scientific, and technical services	other 54	3,566	154	559	2,854
Other nonmanufacturing	21–23, 42–49, 52, 53, 55–81	25,700	1,471	2,225	22,004 i

Because R&D is risky, firms prefer a **portfolio** of RD 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. A **portfolio of R&D projects set up as options has lower risk than a portfolio of unconditional projects.** The option diversifies over time 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.

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 a new 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 without 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 calculate the **expected** marginal gain:
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. The key question becomes how big to make the discovery phase. If have 30 objects, unlikely 1 and not 30. Something in between.

In R&D decision, you want the research project with highest payoff. You have a list of projects but **do not know** the distribution of payoffs. You undertake a project or reject it on the spot.[1] No going back on project. To maximize the probability of getting the best project, divide projects into discovery stage where you use information to select the reservation wage and a decision stage where you choose first project with value > reservation wage. The solution is to take the first 1/e (~ 37%) of projects as discovery, then pick the next one that exceeds the reservation wage. The probability this is the best is 1/ e as N–> infinite. With smaller numbers you do better.

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?

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 $1/n + R^*/n\ [\ln (n-1) - \ln R^*] \sim R^*/n\ (\ln n/R^*) = 1/e \ln e = 1/e$. 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 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.** 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?

F. Thomas Bruss presents 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. Solution 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 $R_s = r_n + r_{n-1} + r_{n-2} + \dots$ until this sum reaches or exceeds 1. This 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	$(5/6)^2$	$(5/6)^3$	$(5/6)^4$	$(5/6)^5$		

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: If Rs ≥ 1, the win probability of stopping on the winning probability ≥ 1/e = 0.378

Example: Accepting a job. What is the chance that an 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. If you have 7 potential offers rk = pk/qk which varies with p.

Period	7	6	5	4	3
ps	1/7	1/6	1/5	¼	1/3
rn	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 on ie 5, 6, or 7. Q_3 = (2/3) (3/4)(4/5) (5/6) (6/7) =2/7 = 0.286 x 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 = + $r_{n-1} + \ldots + r_s \geq 1$ 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 all we need for the main result.

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

What if probability of success unknown? Estimate using sequential updating (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 variant (Bearden, "Comment: A new secretary problem with rank-based selection and cardinal payoffs"Journal of Mathematical Psychology 50 (2006) 58–591) changes payoff from maximizing probability you get best to getting high value applicant. Makes utility more continuous than jump from 0 to 1. "it seems unlikely that utility for selling at some prices slightly below the maximum would be zero. Compared to classical secretary problem, … the payoff scheme presented here is more natural."

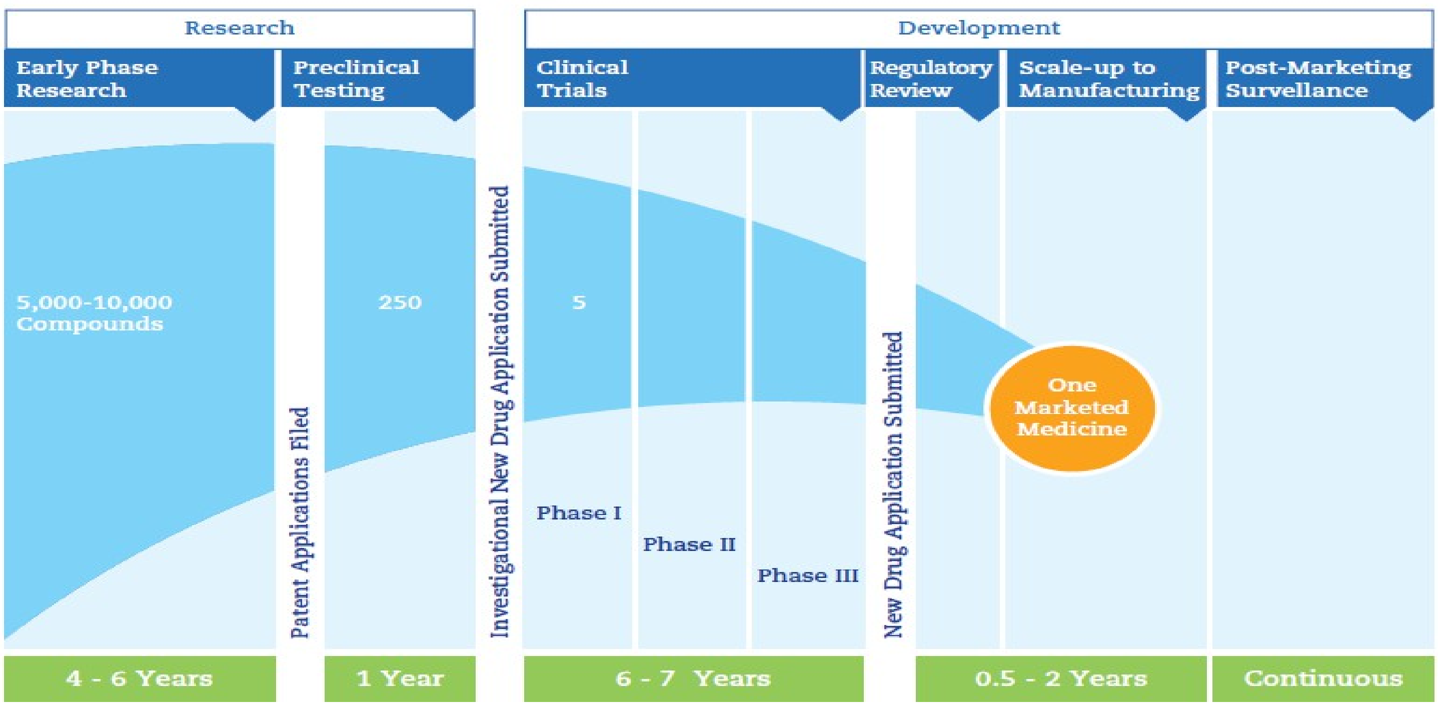
You select nth applicant and get payoff of xt. Estimate how many people you could see **n**; calculate **√n-1** as your discovery set; select first with value > discovery set max. Proven by calculating expected return to a given cutoff period and maximizing expected return. Simple algebra with uniform but should work for other distributions.

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.

People actually 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... interviewed and rejected, only a single applicant is selected, and payoffs increase in the absolute quality of the applicant. Compared to the optimal decision policy ... 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." Bearden, Amnon Rapoport, Ryan O. Murphy, (2006) Sequential Observation and Selection with Rank-Dependent Payoffs: An Experimental Study. Management Science 52(9):1437-1449. Also "Behavioral Decision-making Volume 19, Issue 3 July 2006 Pages 229–250

II. Research in stages, with value viewed as option: Pharma, Top R&D spending and R&D to sales (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 worth many small failures, but cost of hit 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 PHARMA SPENDS FAR MORE ON MARKETING THAN RESEARCH WashPost, 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 reduces uncertainty in benefits/costs so that projects NPV<0 can be worth doing to learn about range of future outcomes.

Variant 1: The value of completed project is $5.00. Project requires 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 sequential 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 analysis works if it tells you are more *likely* to get positive kick. 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 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 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, 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 R&D gives about the ultimate value of R. If information is cheap vs $\sigma 1$- K1, 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 $\rightarrow$ 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 andskews the value distribution. If projects are positively correlated, convexity enhances diversification and lowers overall risk. But if the projects are negatively correlated, portfolio risk is largely independent of diversification; Thus diversification is more effective when projects are positively correlated. Options are more complex instruments for diversification.

PIs do portfolio investment implicitly when 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 2000 survey found that only 9% out of 451 participants use ROA while observing an abandonment rate of 32%. Only Merck 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						
	DCF	VA®	return	del	nalysis	alue	gs value				nulation	ees	lysis	alysis	riod		swers

VIII	Portfolio Health	Response 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

their RI capability... analyzing top-management-driven systems-level approaches. … approaches to developing continuing capability in breakthrough innovation for corporate growth and renewal … 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).

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.

Barlevy, (AER, Sept 2007) focuses on fact that R&D is cyclical 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 holds for physical investment! Invest in the middle of recession so you produce in the coming boom.

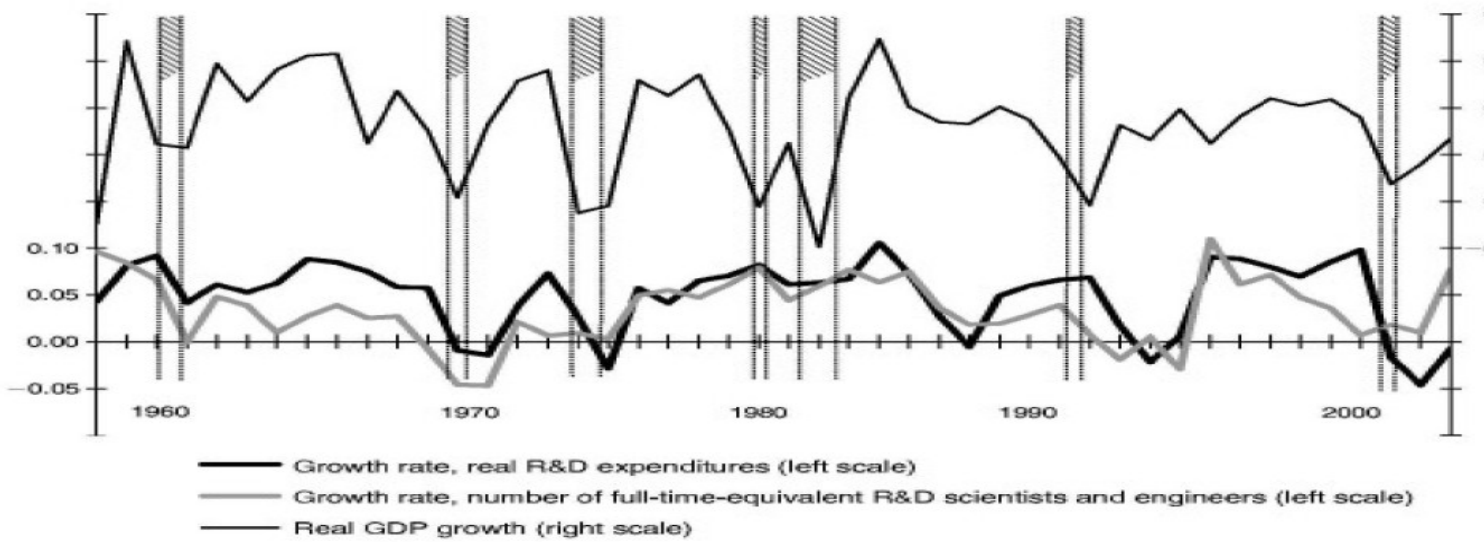


Figure 1. Measures of R&D over the Business Cycle

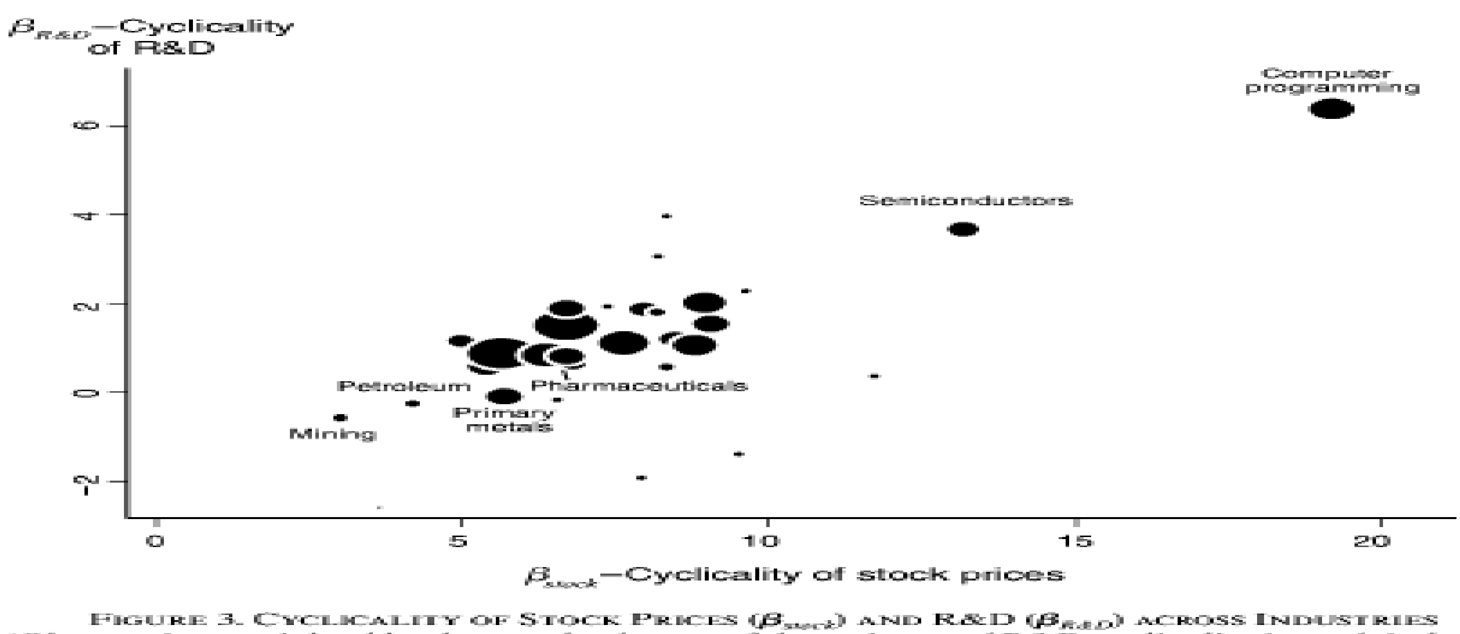


Figure 3. Cyclicality of Stock Prices (β_{stock}) and R&D ($\beta_{R\&D}$) across Industries
(Observations weighted by the standard error of the estimate of R&D cyclicality in each indu

Why is RD cyclical instead of counter-cyclical?

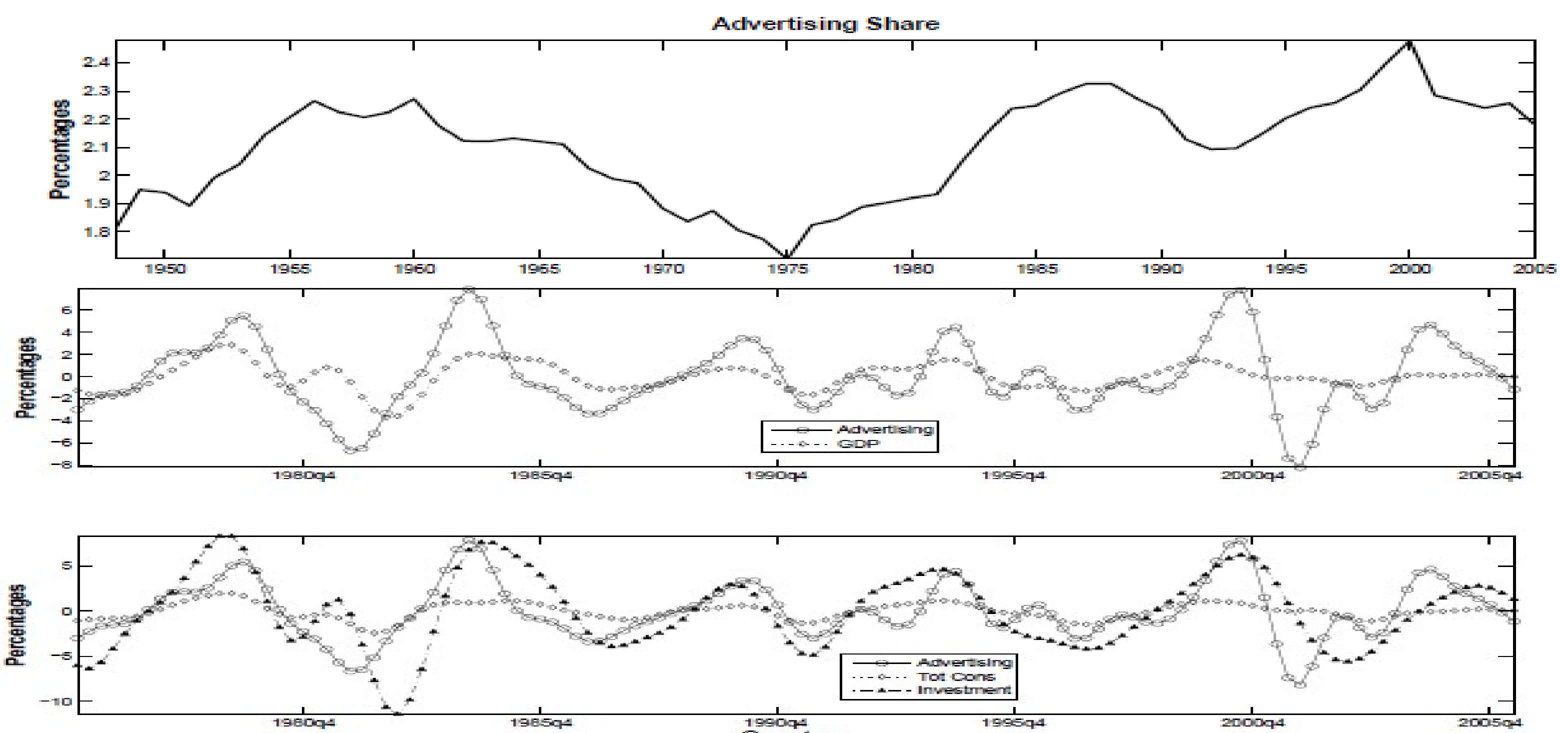
1- Cash flow and budgetary problems cannot explain because firms shift money to keep RD going.
2- RD labor is specialized and difficult to substitute over time so the substitution over time is very weak effect
3- Firms ignore "dynamic externality" that says better to do RD now so others can use it and 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)

NB 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 in Obama Administration boosted 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:



Bloom (AER May 2007) differentiates between adjustment costs associated with changing a stock and adjustments associated with changing a flow and argues that the costs of adjusting the flow are more expensive and thus less responsive to the business cycle . 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.

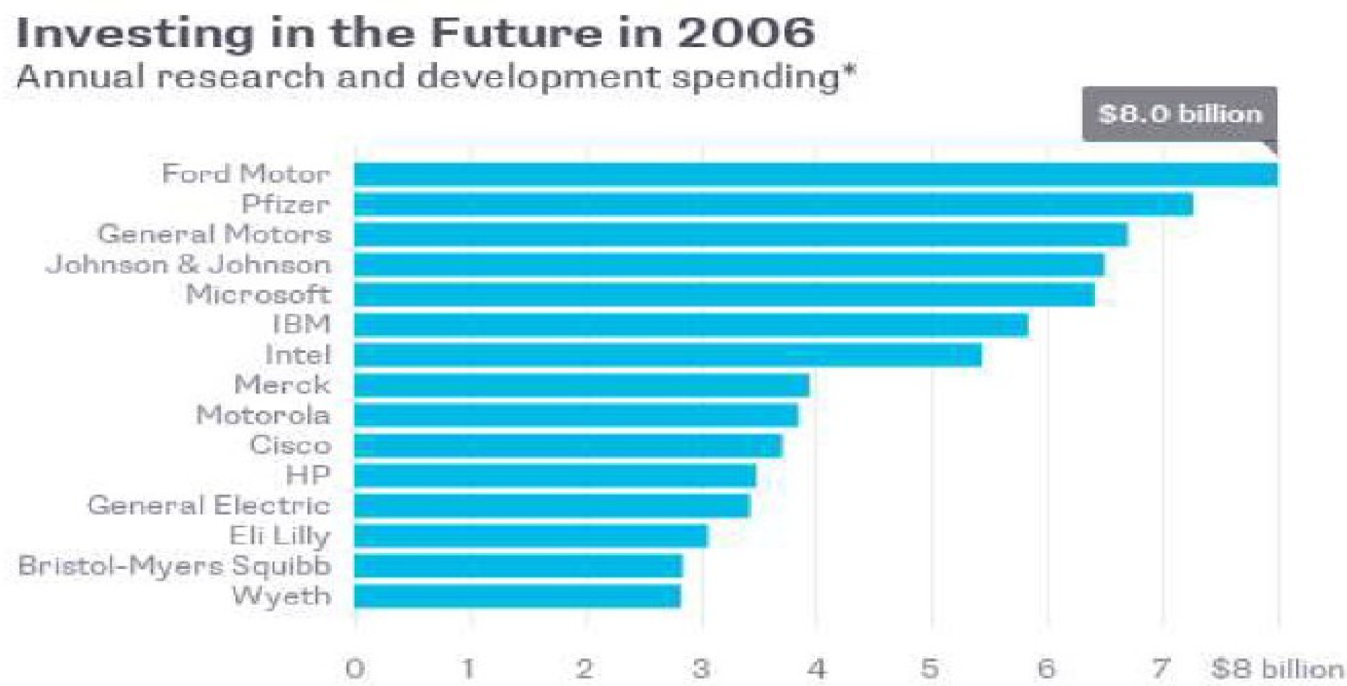
How Particular Firms Rate in R&D – not so easy to do calculations

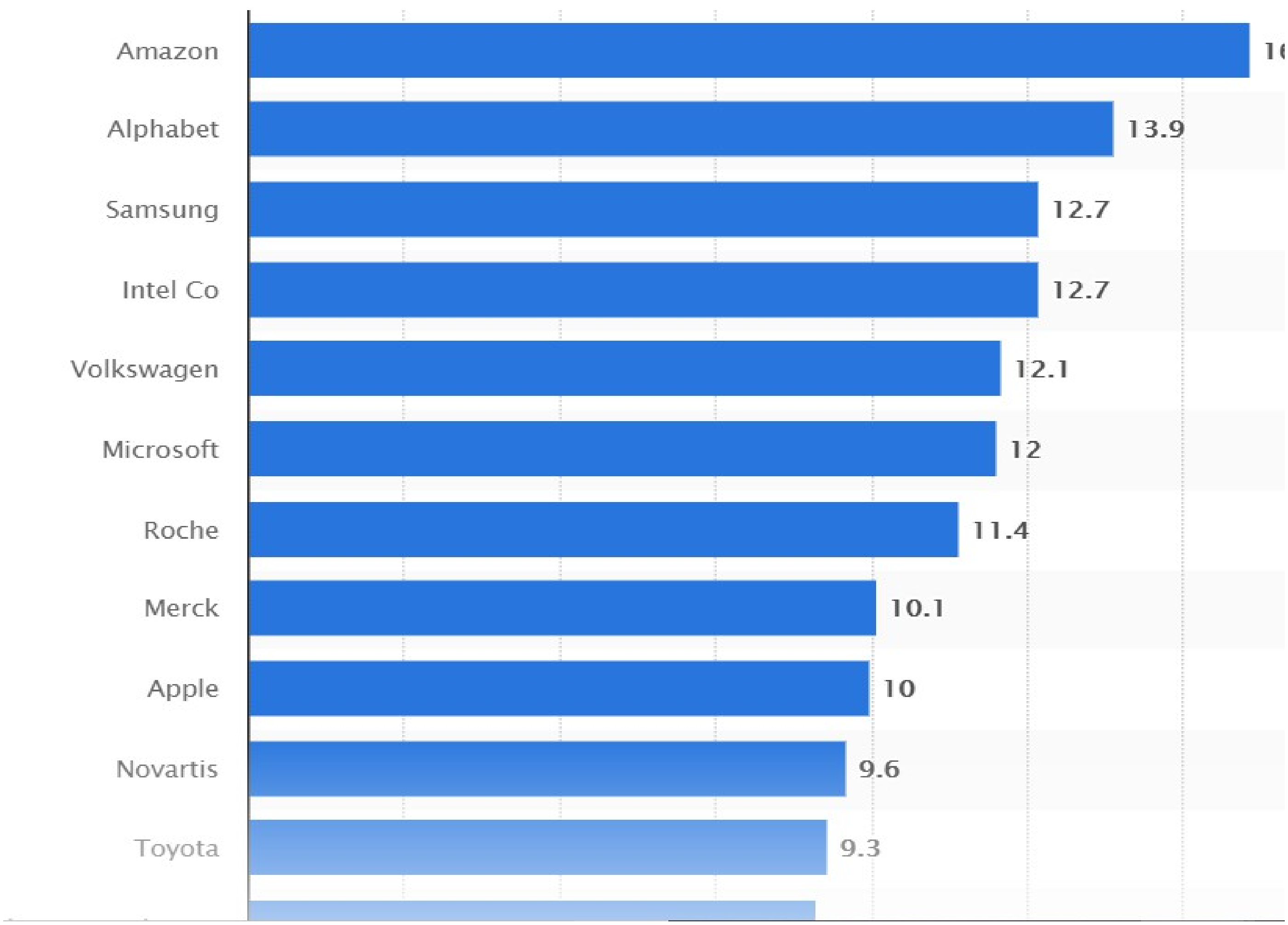
St**rategy, PwC's strategy consulting business,** identified the 1,000 public companies around the world that spent the most on R&D during fiscal year June 30, 2017. Companies had to make their R&D spending numbers public. Subsidiaries more than 50 percent owned by a single corporate parent during the 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. ... 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:

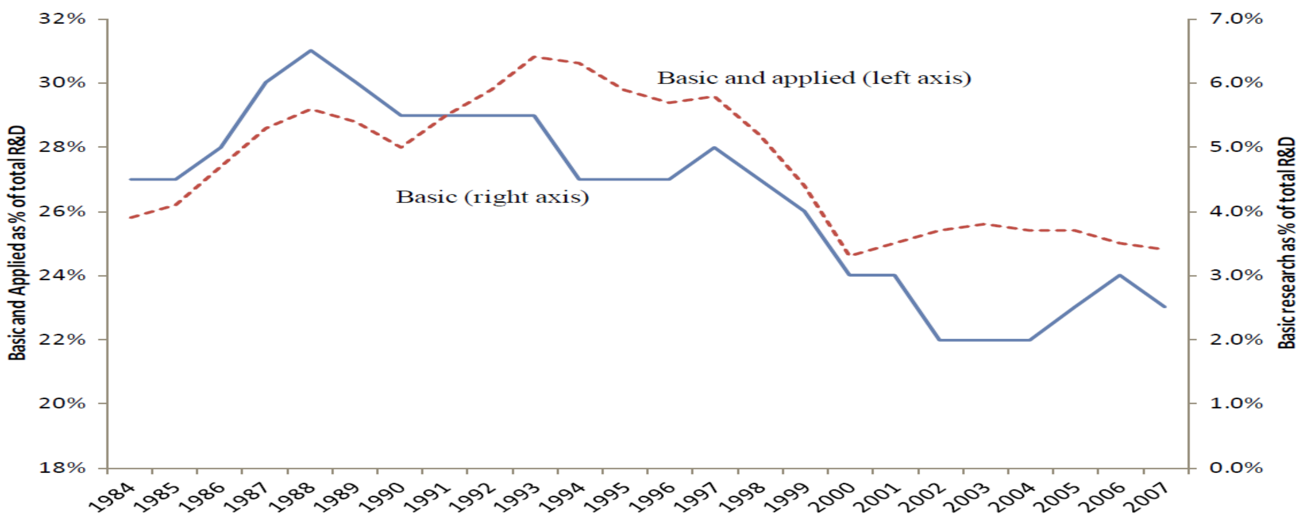




Decline of Corporate Basic R&D: aka death of Bell Labs, etc

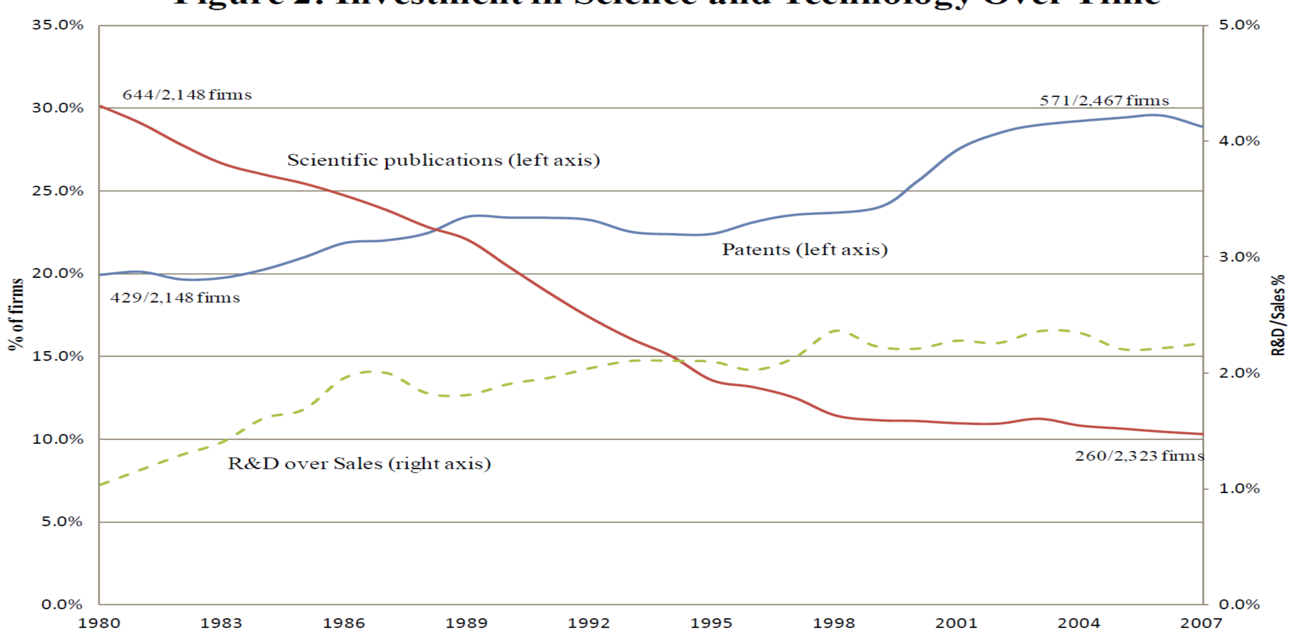
KILLING THE GOLDEN GOOSE? THE DECLINE OF SCIENCE IN CORPORATE R&D Ashish Arora Sharon Belenzon Andrea Patacconi NBER 20902; Back to Basics: Why do Firms Invest in Research? Ashish Arora, Sharon Belenzon, Lia Sheer NBER Working Paper No. 23187

Share of research in total non-Federal R&D



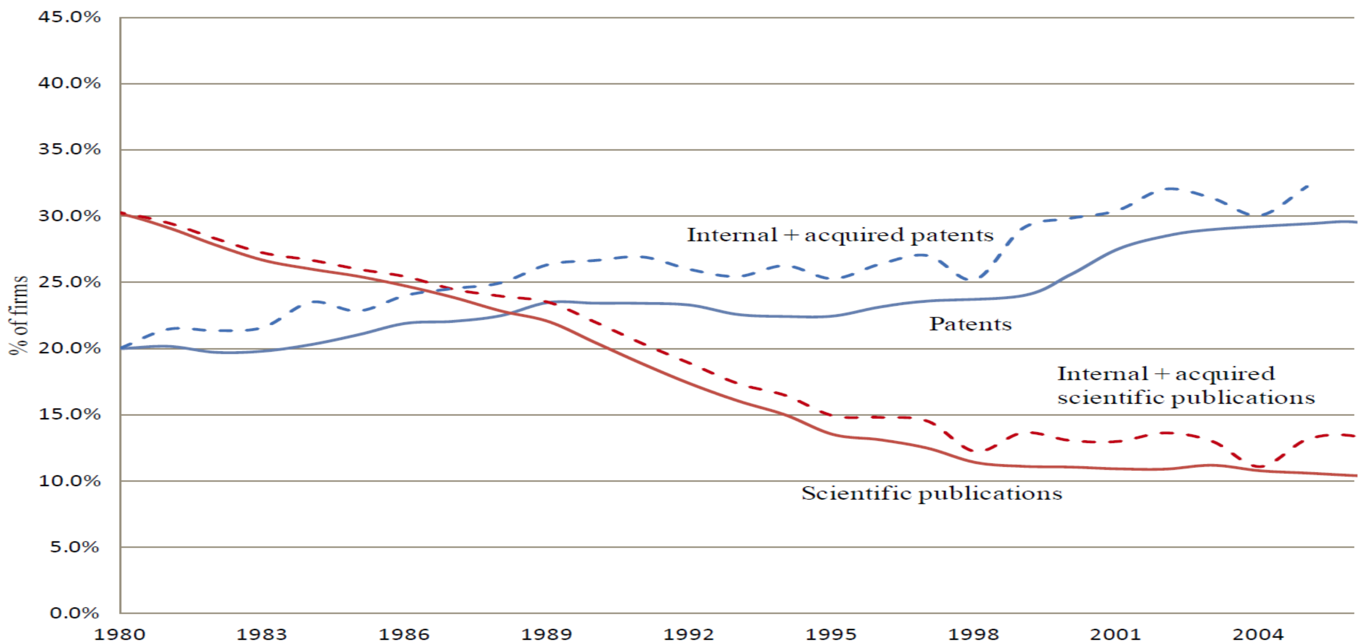
Data source: National Science Foundation/Division of Science Resources Statistics, Survey of Industrial Research and Development: 2007.

Figure 2: Investment in Science and Technology Over Time



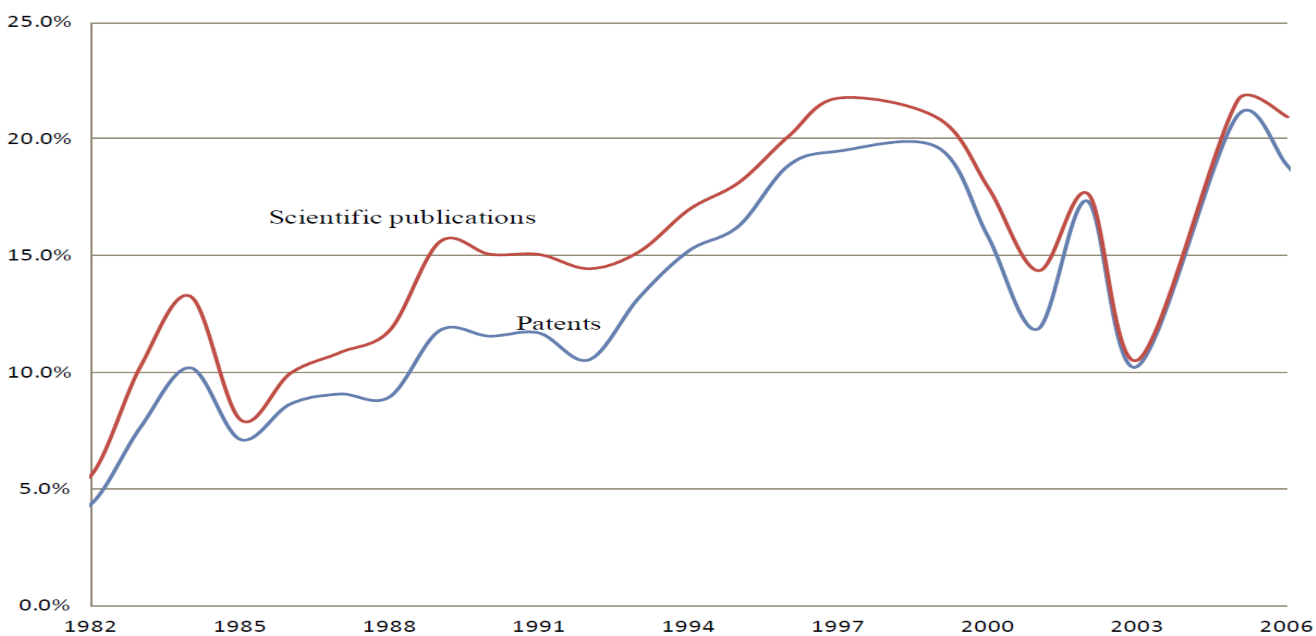
Note: This figure presents the share of publishing and patenting firms of all Compustat firms with at least one year with non-zero R&D expenditures, over time. Data source: Compustat, Web of Science, PatStat.

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



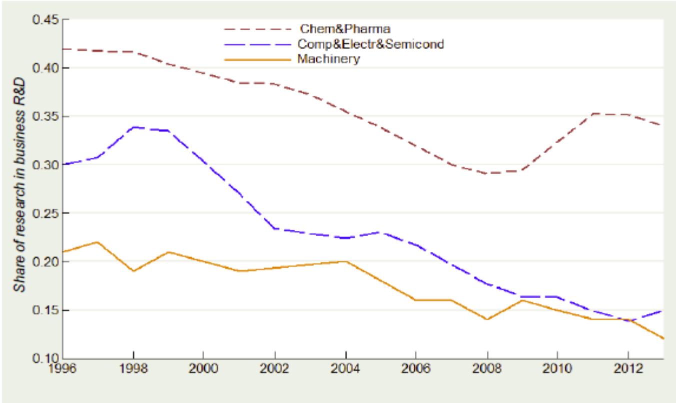
Note: This figure combines internal and acquired publications and patents. The dashed lines present the combined shares. Data source: Compustat, SDC Platinum, Web of Science, PatStat.

Figure 3: Sourcing of Science and Technology Over Time

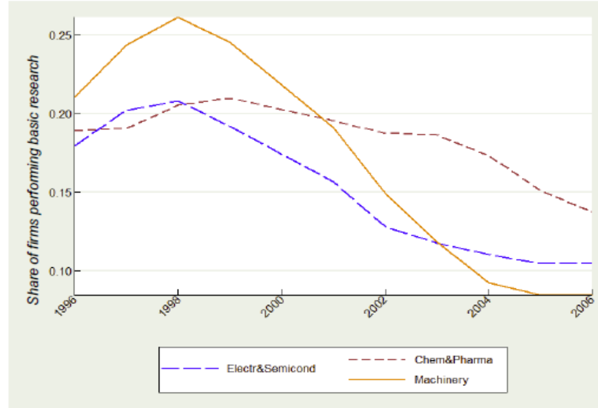


Note: This figure presents the share of publishing firm that acquire targets with scientific publications, and the share of patenting firms that acquire targets with patents, over time (3-year moving average). The dotted line plots the share of fir scientific articles that are coauthored with an external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

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

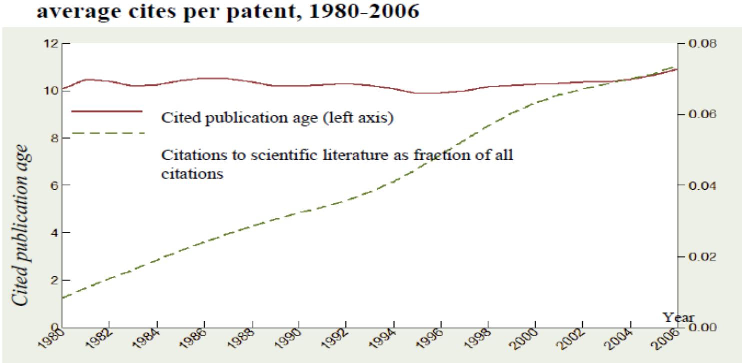


Share of companies performing basic research out of all R&D performers, 1996-2006

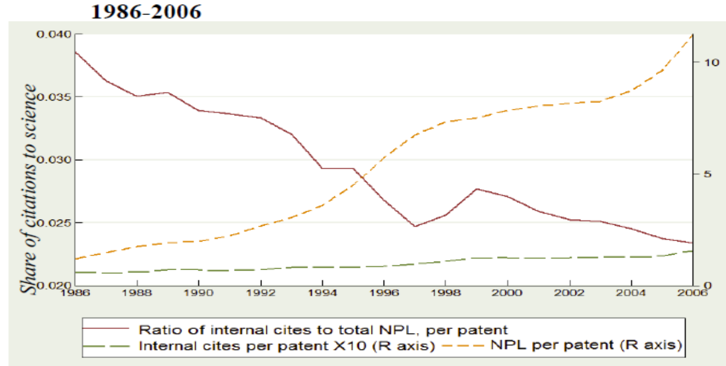


<u>Finding</u>: The decline in corporate research is broad-based, present in a range of industrial sectors

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



Cites to scientific publications by corporate patents, 1986-2006



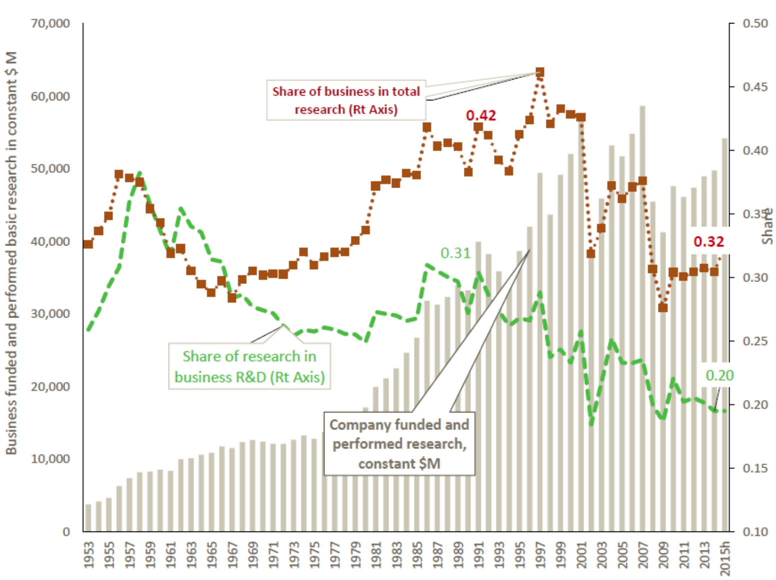
<u>Finding</u>: Corporate patents cite science at higher rates over time; cited science is not older science

<u>Implication</u>: **R remain useful for D**

<u>Finding</u>: Corporate patents cite external science at higher rates over time

<u>Implication</u>: **Firms rely on externally funded R for D, including federally funded R**

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

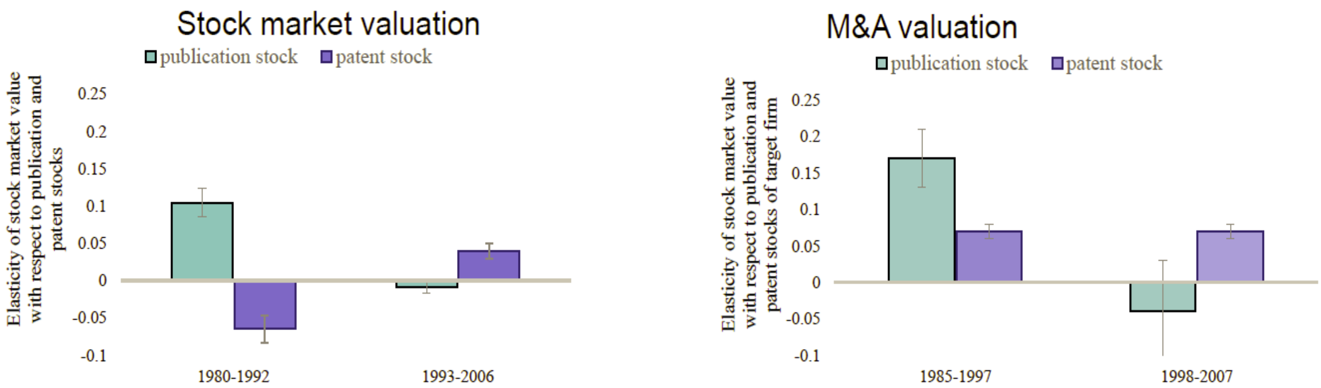


<u>Findings</u>: Firms investing less in research even as overall R&D increases

- 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)

<u>Implication:</u> **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

Also 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... 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.