15.415x Foundations of Modern Finance

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Lecture 15: Capital Asset Pricing Model

Key concepts

- Derivation of CAPM
- Risk and return under CAPM
- CAPM vs APT
- Application of CAPM
- Empirical properties of CAPM betas
- Empirical tests of CAPM
- CAPM and capital budgeting

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Introduction

- Mean-variance portfolio theory analyzes investors' asset demand given asset returns.
  - Diversify to eliminate non-systematic risk.
  - Hold only the risk-free asset and the tangency portfolio.
- How does investors' asset demand determine the relation between assets' risk and return?

The market portfolio

- The market portfolio is the portfolio of all risky assets traded in the market.
- A total of N risky assets. Market capitalization of asset i is:

$$\text{MCAP}_i = (\text{price per share})_i \times (\text{\# of shares outstanding})_i$$

- The total market capitalization of all risky assets is:

$$\text{MCAP}_M = \sum_{i=1}^{N} \text{MCAP}_i$$

- The market portfolio has the following portfolio weights:

$$w_i = \frac{\text{MCAP}_i}{\sum_{j=1}^{N} \text{MCAP}_j} = \frac{\text{MCAP}_i}{\text{MCAP}_M}$$

- We denote the market portfolio by w_M. the vector of market portfolio weights

Derivation of CAPM: assumptions

- All investors invest over the same, single period, $t = 0$ to $t = 1$.
- No other sources of income, entire wealth consists of the portfolio of financial assets. investors' preferences are defined over the return on their portfolios between times 0 and time 1.
- Investors agree on the distribution of asset returns. investors in the model do not disagree with each other.
- Investors have mean-variance preferences. may have different levels of risk aversion, but only care about the first two moments of returns
- There is a risk-free asset:
  - paying interest rate r_F;
  - in zero net supply. some investors may lend, others may borrow
- There are no constraints on portfolios, and no trading costs. financial market is frictionless

market clearing condition

arbitrage opportunity cannot exist in equilibrium

- Demand for assets equals supply in equilibrium.

if risk free asset is in positive net supply, we should include the risk free asset (i.e. treasury) into the market portfolio. $1 treasury investors lend is $1 borrowed by the government. If the government repays these loans from taxes on the same investors, and if you consider the tax liability as a part of each investor's portfolio, it is no longer obvious that there is a positive net supply of the risk free asset in the market.

Derivation of CAPM: implications

1. Every investor puts their money into two pots:
   - the riskless asset; if there are constrains on portfolio (i.e. not allowed to borrow), investor may not hold Tangency portfolio
   - a single portfolio of risky assets, the tangency portfolio.
2. All investors hold the risky assets in same proportions.
   assumption: investors agree on distribution of asset returns.
   - Collectively, they hold the same risky portfolio, the tangency portfolio.
3. Impose market clearing: demand for stocks (the aggregate of investors' portfolios) must equal the supply (the aggregate stock market).
   total demand total supply
   - The tangency portfolio is the market portfolio!
   CML line graph: return to deviation SML line graph: return to beta
   - The market portfolio must be on the CML: it has the highest possible Sharpe ratio (it is mean-variance efficient).

you should use both line graph to determine whether asset properties (return, deviation, beta) are feasible in market
- CML: sharpe ratio higher than tangency/market portfolio: infeasible
- SML: all assets lie on SML

Example: market clearing

- In equilibrium, total asset holdings of all investors must equal the total supply of assets.

- Example: there are only three risky assets, A, B and C. Suppose that the tangency portfolio is

$$w_T = (w_A, w_B, w_C) = (0.25, 0.50, 0.25)$$

- There are only three investors in the economy, 1, 2 and 3, with total wealth of 500, 1000, 1500 dollars, respectively. Their asset holdings (in dollars) are:

Investor	Riskless	A	B	C
1	100	100	200	100
2	200	200	400	200
3	-300	450	900	450
Total	0	750	1500	750

Example: market clearing

- In equilibrium, the total dollar holding of each asset must equal its market value:

$$\text{Market Capitalization of } A = \$750$$

$$\text{Market Capitalization of } \mathrm{B} = \$1{,}500$$

$$\text{Market Capitalization of } \mathrm{C} = \$750$$

- The total market capitalization is

$$750 + 1{,}500 + 750 = \$3{,}000$$

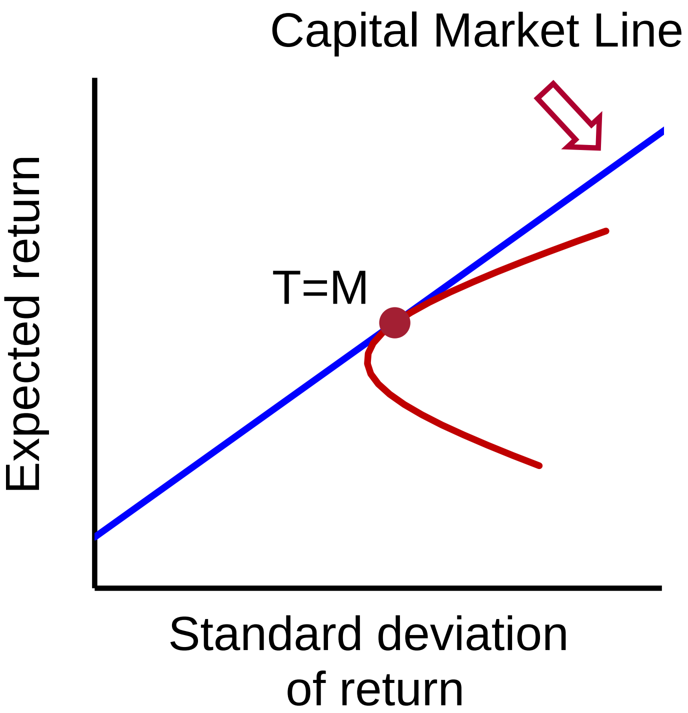
- The market portfolio is the tangency portfolio!

$$w_M = \left(\frac{750}{3{,}000}, \frac{1{,}500}{3{,}000}, \frac{750}{3{,}000}\right) = (0.25, 0.50, 0.25) = w_T$$

Derivation of CAPM

- The marginal contribution of asset i to the market portfolio:
  - return: $\bar{r}_i - r_F$;
  - risk: $\frac{\sigma_{iM}}{\sigma_M}$
- For the market portfolio to be optimal, the marginal return-to-risk ratio (RRR) of all risky assets must be the same:

$$RRR_i = \frac{\bar{r}_i - r_F}{\sigma_{iM}/\sigma_M} = SR_M = \frac{\bar{r}_M - r_F}{\sigma_M}$$



The CAPM

- Re-writing:

$$\frac{\bar{r}_i - r_F}{\sigma_{iM}/\sigma_M} = \frac{\bar{r}_M - r_F}{\sigma_M}$$

we have:

$$\bar{r}_i - r_F = \frac{\sigma_{iM}}{\sigma_M^2}(\bar{r}_M - r_F) = \beta_{iM}(\bar{r}_M - r_F)$$

where $\beta_{iM} = \frac{\sigma_{iM}}{\sigma_M^2}$ is the beta of asset i with respect to the market portfolio.

- This is the CAPM: market beta is equivalent to a factor loading in the APT framework, where the only risk factor is the market return.
  - β_{iM} is a measure of asset i's systematic risk: exposure to the market.
  - $\bar{r}_M - r_F$ gives the premium per unit of systematic risk.

market risk premium is the price of systematic risk.

- The risk premium of an asset equals its systematic risk (β_{iM}) times the price of systematic risk ($\bar{r}_M - r_F$).

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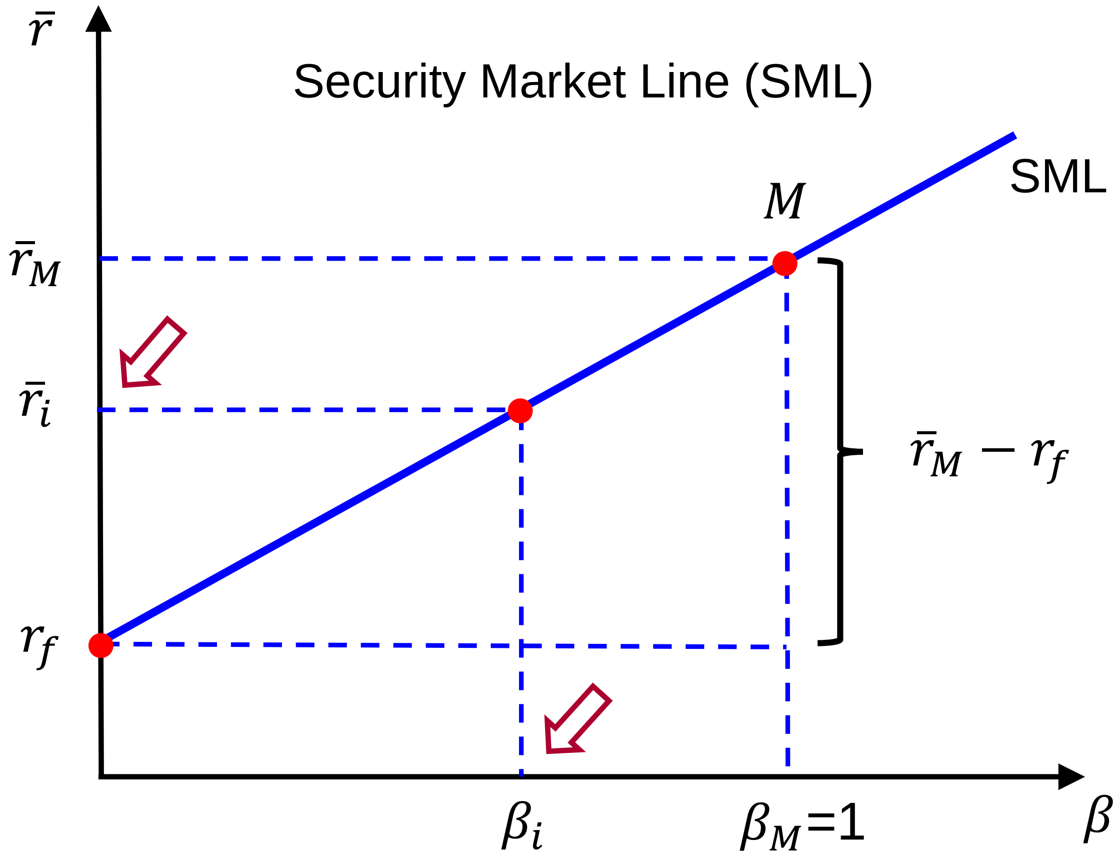
Security Market Line (SML)



- The relation between an asset's premium and its market beta is called the Security Market Line (SML).
- Given an asset's beta, we can determine its expected return.

Example

- Suppose that CAPM holds. The expected market return is 8% and the risk-free rate is 2%. this is true even if this asset is highly volatile. Under CAPM, such an asset has only idiosyncratic risk. And such risk is not compensated by the market.
  - What should be the expected return on a stock with $\beta = 0$?

    2%: only idiosyncratic risk ⇒ risk-free rate of return

  - What should be the expected return on a stock with $\beta = 1$?

    8%: same risk as the market ⇒ same expected return as the market

  - What should be the expected return on a portfolio with the market beta of 0.5?

    $2\% + 0.5 \times (8\% - 2\%) = 5\%$: 50% of market risk ⇒ 50% of risk premium

  - What should be expected return on stock with $\beta = -0.6$?

$\bar{r} = 2\% + (-0.6)(8\% - 2\%) = -1.6\%$: "insurance" against market declines ⇒ negative premium helps lower the overall portfolio risk

Such insurance is costly. And this cost amounts to losing 1.6% in expectation

Risk and return in CAPM

- We can decompose an asset's return into three pieces:

decomposition has nothing to do with the CAPM

$$\tilde{r}_i - r_F = \alpha_i + \beta_{iM}(\tilde{r}_M - r_F) + \tilde{\epsilon}_i$$

CAPM assumptions

The CAPM model makes no assumptions on the factor structure of stock returns. Idiosyncratic components of stock returns don't have to be pairwise uncorrelated. factor structure of APT states that the idiosyncratic return components are uncorrelated with each other

  - $\mathrm{E}[\tilde{\epsilon}_i] = 0;$
  - $\mathrm{Cov}[\tilde{r}_M, \tilde{\epsilon}_i] = 0.$

- Three characteristics of an asset:
  - Alpha: according to CAPM, alpha should be zero for all assets.
  - Beta: measures an asset's systematic risk.
  - Sigma = $\mathrm{SD}(\tilde{\epsilon}_i)$: measures non-systematic risk.

Alpha

$$\tilde{r}_i - r_F = \boxed{\alpha_i} + \beta_{iM}(\tilde{r}_M - r_F) + \tilde{\epsilon}_i$$

- According to CAPM, alpha should be zero for all assets.
- Alpha measures an asset's return in excess of its risk premium according to CAPM.
- What to conclude if we find an asset with a positive (or negative) alpha?
  - Check estimation error; past return data are noisy, time-varying distribution of returns
  - Past value of α may not predict its future value; It is a lot easier to find alpha in past data than to realize it in actual investments going forward.
  - Positive α may be compensating for other risks; alpha may not represent a free lunch
  - Trading frictions, taxes,… assumption is violated

transaction costs, constraints on positions,

Alpha and portfolio choice

- Suppose that asset i violates the CAPM:

$$\tilde{r}_i - r_F = \alpha_i + \beta_{iM}(\tilde{r}_M - r_F) + \tilde{\epsilon}_i,$$

where idiosyncratic shocks are mutually uncorrelated.

- Consider a mean-variance optimizing investor.
  - How would the portfolio of this investor deviate from the market portfolio?
  - Compute the highest Sharpe ratio an investor can achieve in this market. than what is offered by the market portfolio.

Alpha and portfolio choice

$$\tilde{r}_i = r_F + \alpha_i + \beta_{iM}(\tilde{r}_M - r_F) + \tilde{\epsilon}_i$$

- Construct a portfolio P, $\$1$ total investment:
  - Long \$1 of asset i; mispriced asset
  - -$\$\beta_{iM}$ units of the market portfolio;
  - $\$\beta_{iM}$ in the risk-free asset.

$$\tilde{r}_P = \tilde{r}_i - \beta_{iM}(\tilde{r}_M - r_F) = r_F + \alpha_i + \tilde{\epsilon}_i$$

- Note that return on P is uncorrelated with the market return; $SR_P = \alpha_i/\sigma_{\epsilon_i}$.
  excess return/ deviation
- Construct the tangency portfolio using portfolios M and P:

$$w_M = \lambda \frac{\bar{r}_M - r_F}{\sigma_M^2}, \qquad w_P = \lambda \frac{\bar{r}_P - r_F}{\sigma_P^2} = \lambda \frac{\alpha_i}{\sigma_{\epsilon_i}^2}$$

- Sharpe ratio of the tangency portfolio:

general equation: applies to portfolios with uncorrelated assets

$$SR_T = \sqrt{SR_M^2 + SR_P^2}$$

indicate the magnitude of CAPM violation

Alpha and portfolio choice

Derivation of the Sharpe ratio of the tangency portfolio

$$\boxed{\tilde{r}_P = r_F + \alpha_i + \tilde{\epsilon}_i}$$

- Start with the weights of the tangency portfolio:

$$\boldsymbol{w_T = \lambda\, \Sigma^{-1} \bar{x}} \qquad w_M = \lambda \frac{\bar{r}_M - r_F}{\sigma_M^2}, \qquad w_P = \lambda \frac{\bar{r}_P - r_F}{\sigma_P^2} = \lambda \frac{\alpha_i}{\sigma_{\epsilon_i}^2}$$

- Compute expected excess return and variance of the tangency portfolio:

$$\bar{r}_T - r_F = w_M(\bar{r}_M - r_F) + w_P(\bar{r}_P - r_F) = \lambda \frac{(\bar{r}_M - r_F)^2}{\sigma_M^2} + \lambda \frac{(\alpha_i)^2}{\sigma_{\epsilon_i}^2}$$

$$\sigma_T^2 = w_M^2 \sigma_M^2 + w_P^2 \sigma_P^2 = \lambda^2 \frac{(\bar{r}_M - r_F)^2}{\sigma_M^2} + \lambda^2 \frac{(\alpha_i)^2}{\sigma_{\epsilon_i}^2} = \lambda(\bar{r}_T - r_F)$$

Alpha and portfolio choice

Derivation of the Sharpe ratio of the tangency portfolio

- Start with the weights of the tangency portfolio:

$$w_M = \lambda \frac{\bar{r}_M - r_F}{\sigma_M^2}, \qquad w_P = \lambda \frac{\bar{r}_P - r_F}{\sigma_P^2} = \lambda \frac{\alpha_i}{\sigma_{\epsilon_i}^2}$$

- Compute expected excess return and variance of the tangency portfolio:

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$$\sigma_T^2 = w_M^2 \sigma_M^2 + w_P^2 \sigma_P^2 = \lambda^2 \frac{(\bar{r}_M - r_F)^2}{\sigma_M^2} + \lambda^2 \frac{(\alpha_i)^2}{\sigma_{\epsilon_i}^2} = \lambda(\bar{r}_T - r_F)$$

- Sharpe ratio of the tangency portfolio:

$$SR_T^2 = \frac{(\bar{r}_T - r_F)^2}{\sigma_T^2} = \frac{1}{\lambda}(\bar{r}_T - r_F)$$

$$\boxed{\sigma_T^2 = \lambda(\bar{r}_T - r_F)}$$

Alpha and portfolio choice

Derivation of the Sharpe ratio of the tangency portfolio

- Start with the weights of the tangency portfolio:

$$w_M = \lambda \frac{\bar{r}_M - r_F}{\sigma_M^2}, \qquad w_P = \lambda \frac{\bar{r}_P - r_F}{\sigma_P^2} = \lambda \frac{\alpha_i}{\sigma_{\epsilon_i}^2}$$

- Compute expected excess return and variance of the tangency portfolio:

$$\bar{r}_T - r_F = w_M(\bar{r}_M - r_F) + w_P(\bar{r}_P - r_F) = \underbrace{\lambda \frac{(\bar{r}_M - r_F)^2}{\sigma_M^2} + \lambda \frac{(\alpha_i)^2}{\sigma_{\epsilon_i}^2}}$$

$$\sigma_T^2 = w_M^2 \sigma_M^2 + w_P^2 \sigma_P^2 = \lambda^2 \frac{(\bar{r}_M - r_F)^2}{\sigma_M^2} + \lambda^2 \frac{(\alpha_i)^2}{\sigma_{\epsilon_i}^2} = \lambda(\bar{r}_T - r_F)$$

- Sharpe ratio of the tangency portfolio:

$$SR_T^2 = \frac{(\bar{r}_T - r_F)^2}{\sigma_T^2} = \frac{1}{\lambda}(\bar{r}_T - r_F) = \frac{(\bar{r}_M - r_F)^2}{\sigma_M^2} + \frac{(\alpha_i)^2}{\sigma_{\epsilon_i}^2} = SR_M^2 + SR_P^2$$

$$SR_T = \sqrt{SR_M^2 + SR_P^2}$$

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CAPM vs APT

- The CAPM equation is identical to the APT equation with a single factor. But the two theories have important differences.

	CAPM	APT
Preferences	Mean-variance preferences	Prefer more to less ⇒ absence of arbitrage
Factor structure in returns	Not needed	Required
Exact or approximate?	Applies exactly to all assets	Holds exactly only for well-diversified portfolios. Approximate for individual assets
Identity of systematic risk	Market return	Multiple risk factors, not identified explicitly by the theory

A small number of assets may violate the APT equation without creating arbitrage in the market.

CAPM vs APT

- What if returns have a multi-factor structure, can the CAPM still hold?
- Yes! Under the CAPM, market return still prices all assets, including the APT factors themselves.

The CAPM relation would still hold under the CAPM assumptions. the market factor would price all of the APT factors according to the CAPM formula.

- The same fundamental insight in both models:

The only component of total risk relevant for pricing is the systematic risk.

only systematic risk is compensated in the market. Idiosyncratic risk does not carry a risk premium.

Optimizing investors choose to hold the market portfolio, which provides the best possible risk return trade-off. Idiosyncratic risk of an individual stock ends up diversified within the market portfolio.

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Applications of CAPM

- Required rates of return on IBM and Dell.
  - Use the value-weighted stock portfolio as a proxy for the Market.
  - Regress historic returns of IBM and Dell on the returns on the value-weighted portfolio. Suppose the beta estimates are:

$$\beta_{IBM,VW} = 0.8 \text{ and } \beta_{Dell,VW} = 1.3$$

  - Use historic excess returns on the value weighted portfolio of all stocks to estimated average market premium, suppose it is $\bar{r}_{VW} - r_F = 6\%$.
  - Obtain the current riskless rate. Suppose it is $r_F = 2\%$.
  - Applying CAPM:

$$\bar{r}_{IBM} = r_F + \underbrace{\beta_{IBM,VW}}_{\text{factor loading}} \overbrace{(\bar{r}_{VW} - r_F)}^{\text{factor risk premium}} = 2\% + 0.8 \times 6\% = 6.8\%$$

- The expected rate of return on IBM (under CAPM) is 6.8%. Similarly, the expected rate of return on Dell is 9.8%.

Advantages of using CAPM and APT

- Historical averages of returns on individual stocks are poor estimates of expected returns going forward:
  - Short samples; too short to estimate the expected returns with necessary precision
  - Time-variation in risk and expected returns.
- Can estimate betas more precisely than expected returns.
- CAPM and APT allow us to use firm-level beta estimates (relatively precise) and market or factor risk premia (long sample).
- Estimates of future expected returns on an asset are based on its systematic risk, not on the average of its past returns.

use the historical average returns to estimate the market risk premium, this is a more tractable problem than estimating expected returns on the individual stocks.
- market portfolio is less volatile. It has no idiosyncratic risk
- relatively long historical return series for the market
- distribution of returns on the market portfolio may not be constant over time, it is arguably more stable than for individual stocks.

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Beta estimates: daily data

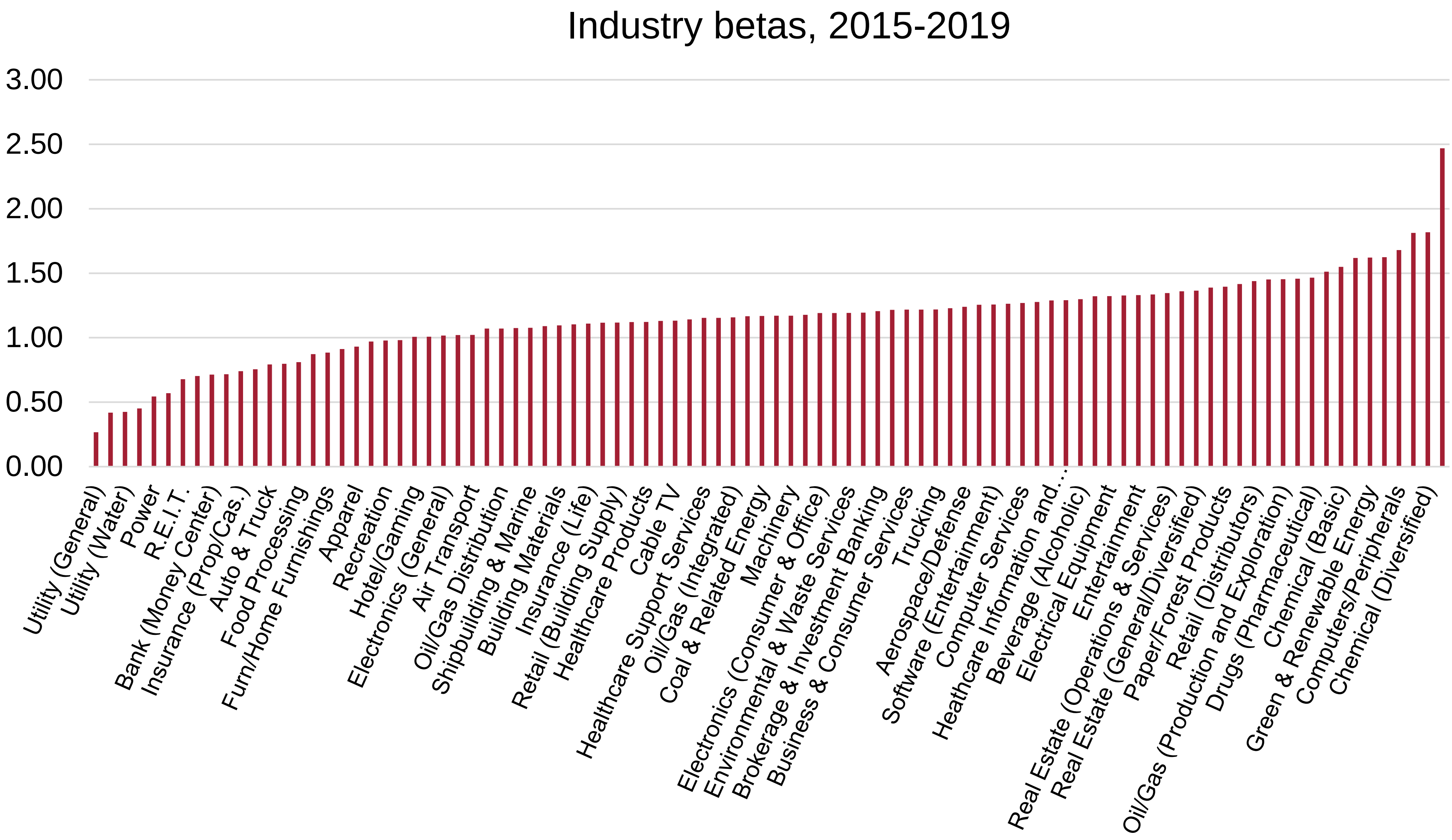
average beta appears to be close to 1.beta of any portfolio is a weighted average of individual betas, and the beta of the market portfolio is 1.

Regression with daily data, 1/4/19—6/5/19

Equity betas measured in the stock market

Company	Beta	Total SD of return (daily, %)	SD of idiosyncratic risk (daily, %)
GENERAL MOTORS CORP	1.29	1.74	1.37
BOEING CO	1.44	1.79	1.37
BRISTOL MYERS SQUIBB CO	1.54	2.05	1.64
DELTA AIRLINES INC	1.28	1.78	1.46
HEWLETT PACKARD CO	1.56	2.43	2.10
DOW CHEMICAL CO	1.43	3.17	2.97
EXXON CORP	0.88	1.12	0.85
MERCK&CO INC	0.72	1.17	1.02
HOME DEPOT INC	0.79	1.12	0.92
MC DONALDS CORP	0.34	0.78	0.73
MICROSOFT CORP	1.33	1.37	0.85
APPLE COMPUTER INC	1.63	1.92	1.40
GOOGLE INC	1.22	1.59	1.26
WAL MART INC	0.36	0.92	0.87
JPMORGAN CHASE&CO	0.98	1.20	0.90

Industry betas



Industry betas

- Why do industry betas differ?

- Fundamental differences:

  not stable

  - Cyclicality of demand, more cyclical demand for their output tend to have more cyclical cash flows, which contributes to their higher market betas.

    debt market

  - Exposure to credit market risk, other aggregate shocks…

- Leverage: relation between the level of leverage and equity betas across firms is far from straightforward.

  debt

  - Leverage raises equity betas relative to asset betas (enterprise betas).

  - Leverage level is a choice, related to fundamental risk.

firms with more stable cash flows tend to use more debt in their capital structure. This means that firms using more leverage tend to have lower enterprise betas or asset betas.

Leverage: equity beta vs asset betas

- Firm ABC has debt and equity: debt-to-equity ratio of 0.65.
- Assume that ABC's debt has a rating of A and a beta of 0.10.
- The beta of ABC equity is 0.73.

$$\bar{r_1} - r_f = \beta_1(\bar{r_M} - r_f) \quad (1)$$

$$\bar{r_2} - r_f = \beta_2(\bar{r_M} - r_f) \quad (2)$$

- What is the beta of ABC's assets (it's enterprise beta)?

$$\alpha*(1)+(1-\alpha)*(2) : \alpha\bar{r_1}+(1-\alpha)\bar{r_2}-r_f = (\alpha*\beta_1+(1-\alpha)*\beta_2)(\bar{r_M}-r_f) \quad (3)$$

- The assets of the firm serve to pay all investors, and so:

$$A = E + D$$

- Thus, the firm's assets are a portfolio of its equity and debt:

$$\beta_A = \frac{E}{E+D}\beta_E + \frac{D}{E+D}\beta_D$$

$$= \frac{1}{1+0.65}(0.73) + \frac{0.65}{1+0.65}(0.10) = 0.48$$

0.73 > 0.48
leverage works!

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Empirical test of the CAPM: design

- Follow Black, Jensen, and Scholes (1972).
- For each security i and month t, define excess returns: $xr_t^i = r_t^i - r_{F,t}^{1M}$
  - r_t^i is the return from the start to end of month t .
  - $r_{F,t}^{1M}$ is the one-month treasury bill rate at the start of the month. This is our 1-month “risk-free” rate.
- For every (security, month) pair, estimate beta on a 60-month window, ~~conditional on 24 non-missing month observations.~~

why portfolio? reduce the effect of noise and time-varying of single stock

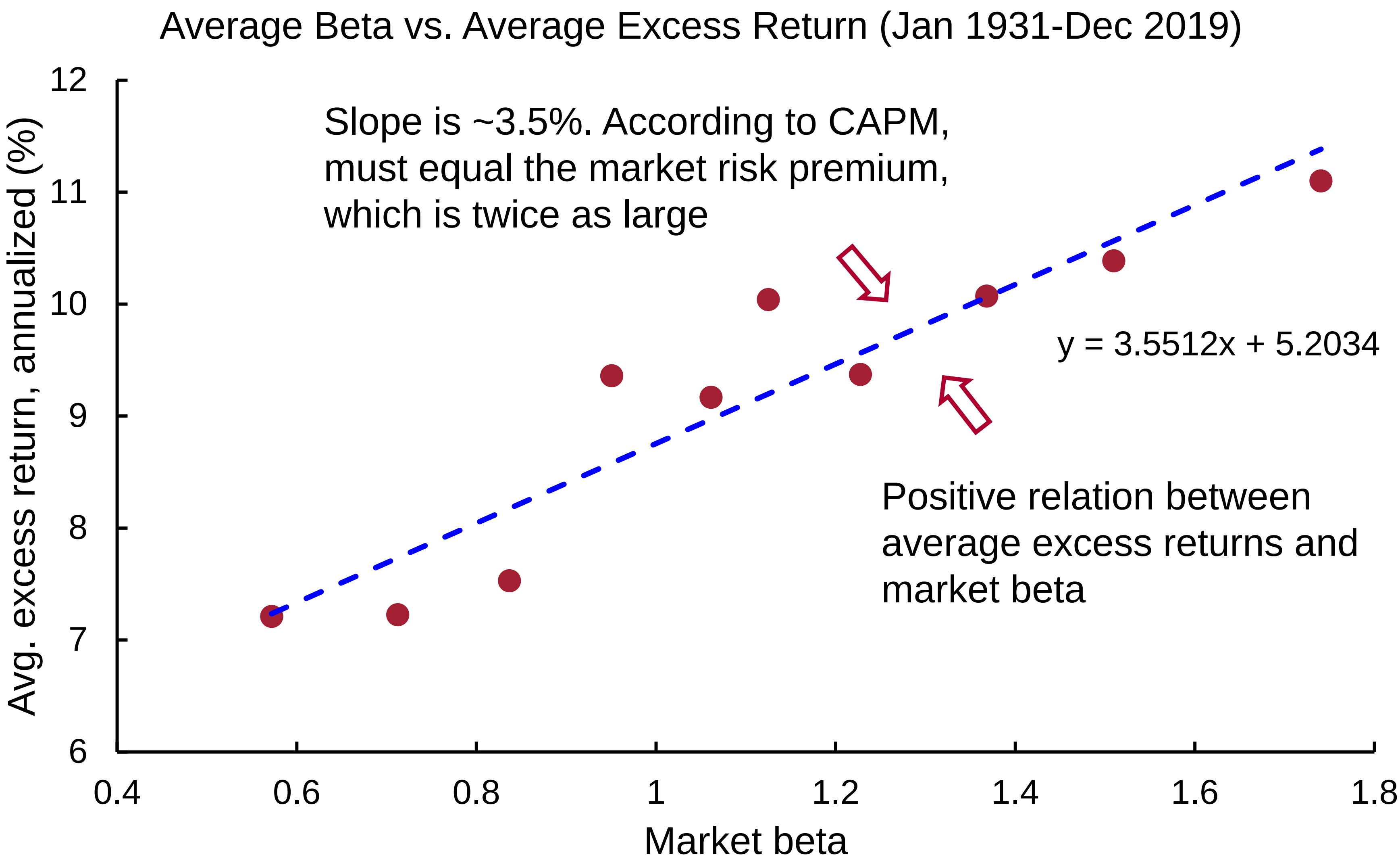
- On January 1st of every year t, create ten portfolios by sorting on betas estimates recorded in December of the previous year $t-1$.
- For each portfolio, compute value-weighted excess return xr_t^p after portfolio formation.

Empirical test of the CAPM: design

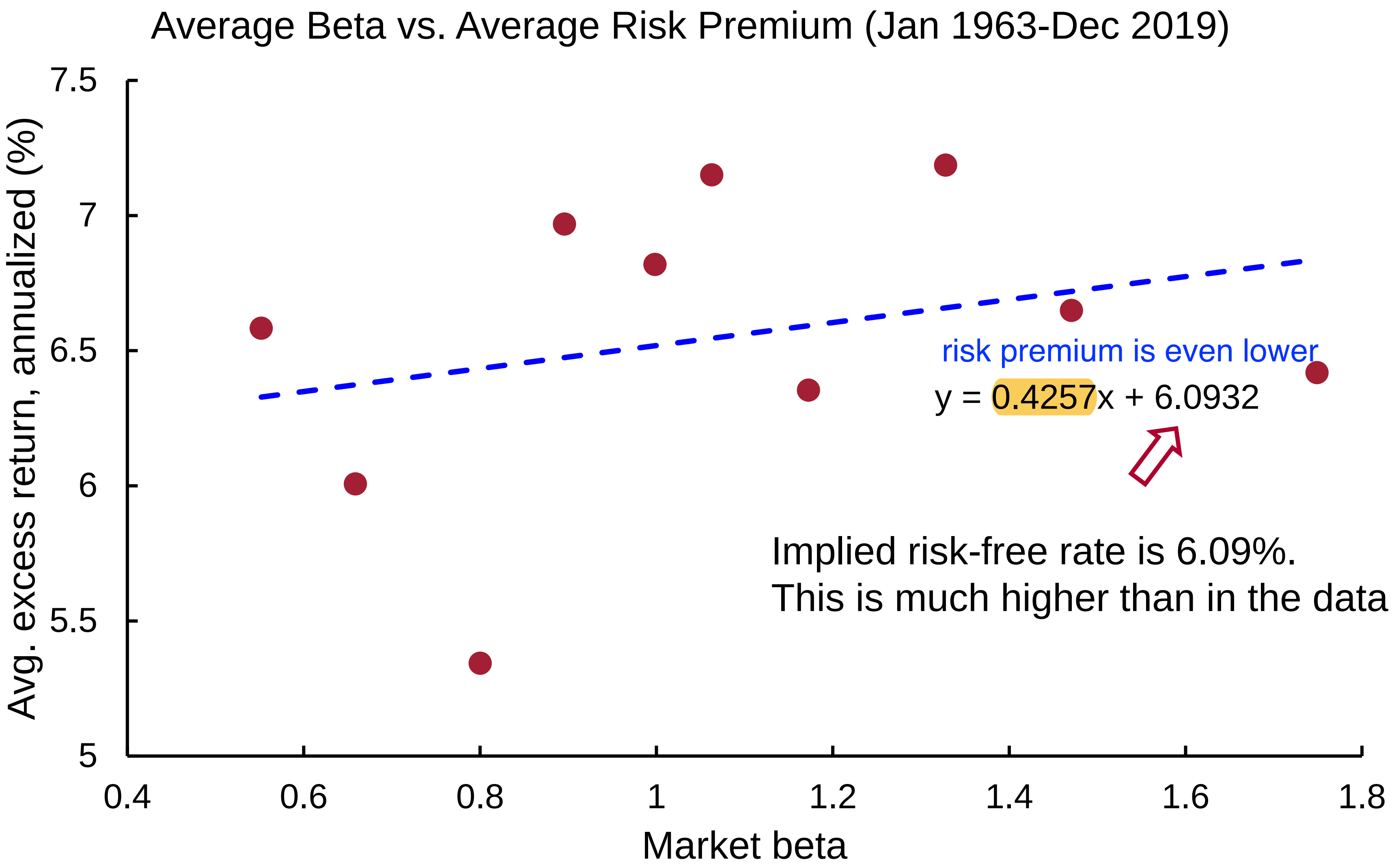
- For each portfolio, estimate the portfolio beta β^p by regressing portfolio excess returns xr_t^p on the value-weighted market excess returns over the full sample.

- For each portfolio, compute the time-series average of excess monthly returns, xr_t^p.

Estimated SML is too flat



Estimated SML is really flat…

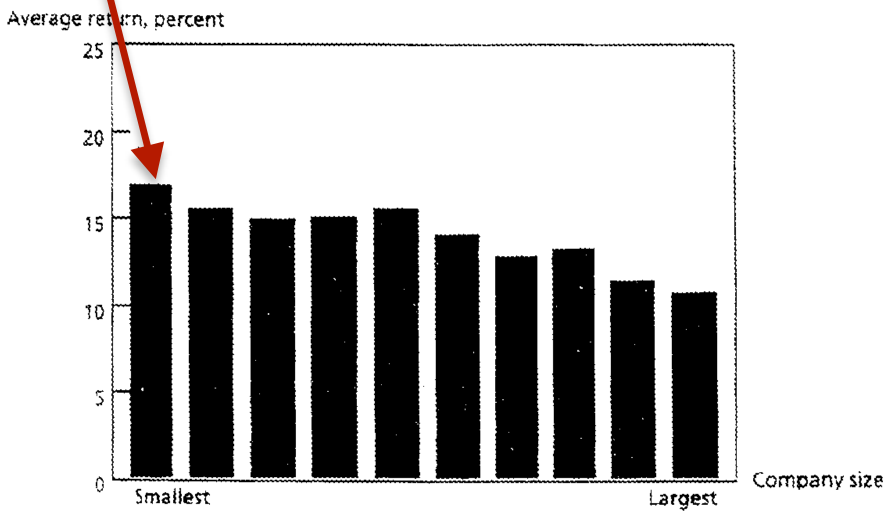


Firm size and book-to-market

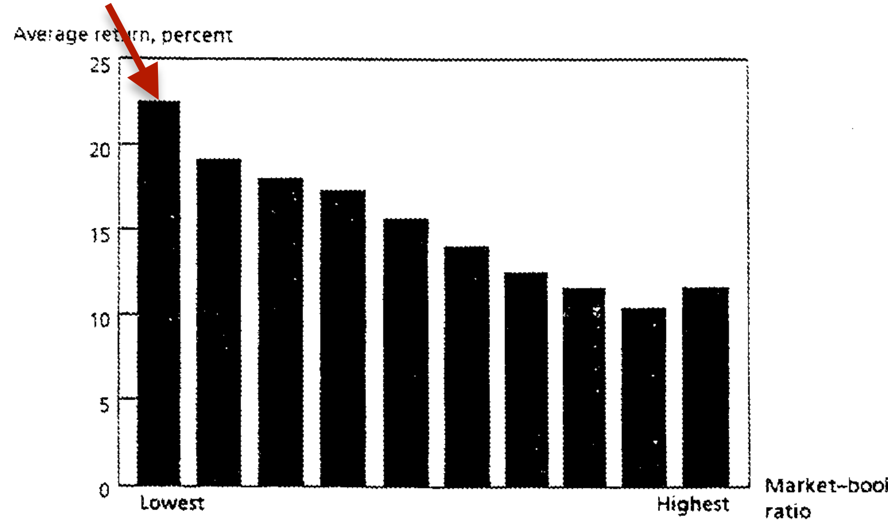
Other examples of CAPM violations

- Firm characteristics seem to predict future returns.

small stock



value stock



(Source: G. Fama and K. French, 1992,
"The Cross-Section of Expected Stock Returns," *Journal of Finance*)

- Since mid-1960s:
  - Small stocks outperformed large stocks.
  - Stocks with low ratios of market-to-book value outperformed stocks with high ratios.

Interpretation

- Empirical failures of the CAPM suggest two main alternative interpretations:

  mispricing is easy to find. It is then puzzling that it does not get arbitraged away

  - Small stocks, high B/M stocks, low-beta stocks, etc., are mispriced;

Perhaps it is difficult to take advantage of such mispricing because of market frictions, such as relatively low liquidity of small stocks.

  - The CAPM does not measure risk properly – there are missing risk factors. Such missing factors would then manifest themselves as CAPM alphas.

- There exists a significant body of work on this topic, the question is still open.

- It is difficult to argue that CAPM alphas can be fully explained by additional risk factors, but evidence suggests that the stock market return is not the only risk factor compensated with the risk premium.

  APT

- Multi-factor models may offer a better description of the risk-return relation.

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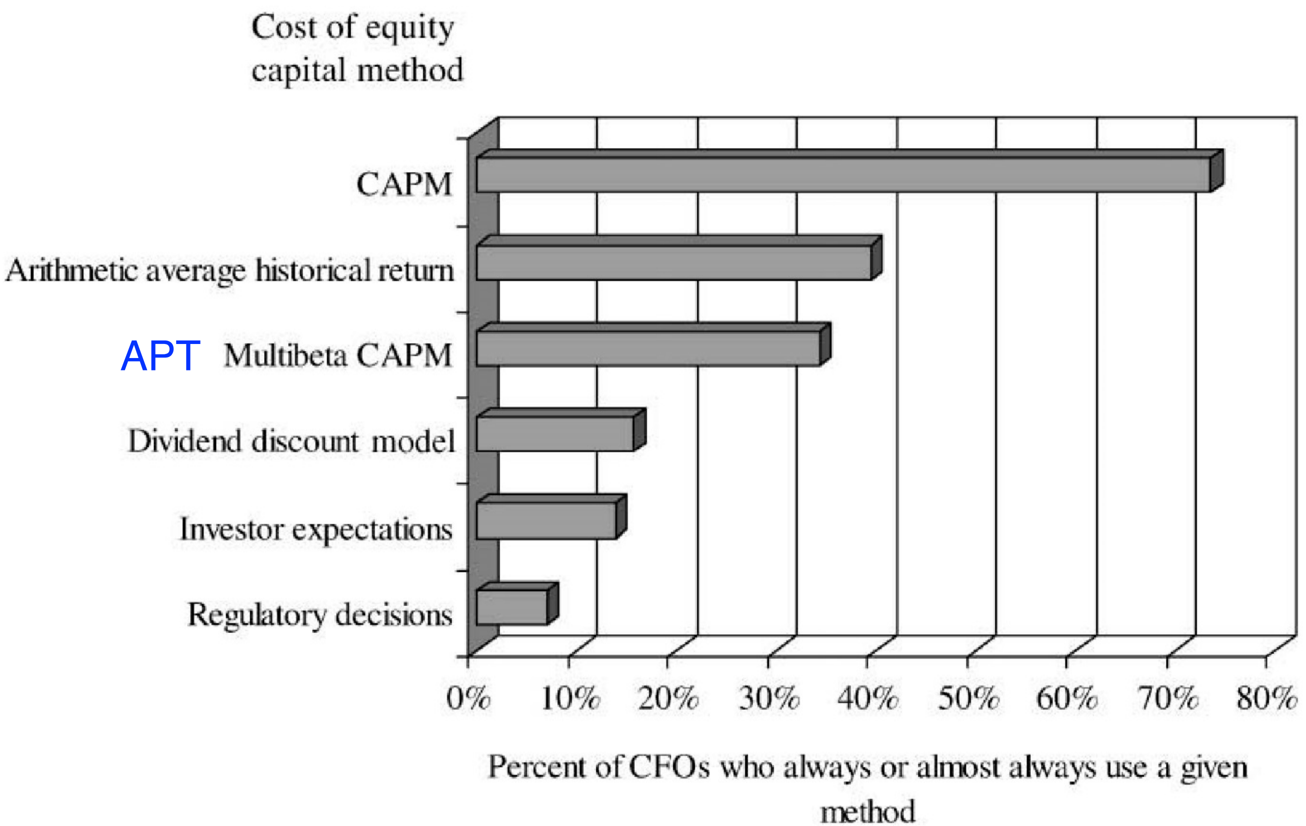
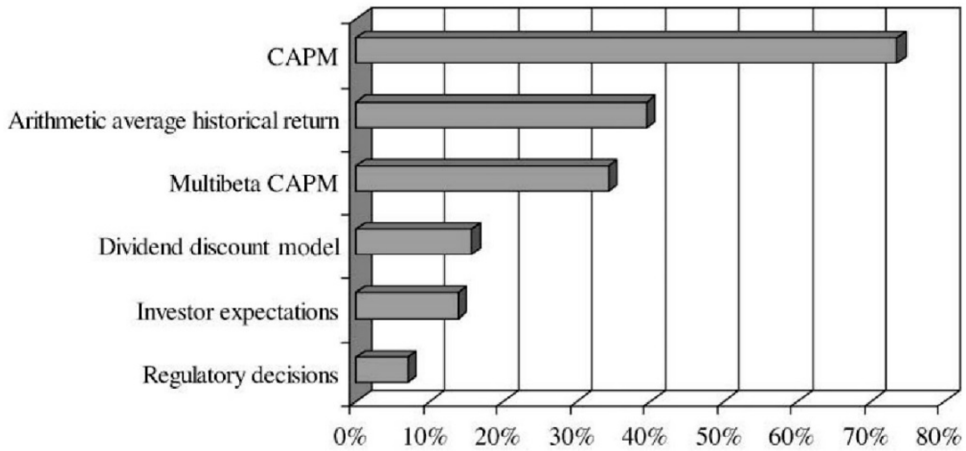


Fig. 3. Survey evidence on the popularity of different methods of calculat the cost of equity capital. We report the percentage of CFOs who always or almost always use a particular technique. CAPM represents the capital asset pricing model. The survey is based on the responses of 392 CFOs.

J. Graham and C. Harvey, "The theory and practice of corporate finance: evidence from the field," Journal of Financial Economics (2001) 187-243.

CAPM and capital budgeting



- Large firms, public firms, and low-leverage firms are more likely to use CAPM.
- Multibeta CAPM (APT). Additional risk factors:
  - Foreign exchange rate, interest rate, GDP, inflation risk, … ;
  - Large firms: FX risk most prominent;
  - Small firms: interest rate risk most prominent.

All models are wrong but some are useful

- CAPM is the leading model for capital budgeting.
- When valuing projects, forecast long-term discount rates.
- Many CAPM violations tend to be short-lived, transient.
- CAPM is not perfect, but a useful benchmark model.

all models are wrong, but some are useful

if CAPM holds, it can be used to estimate discount rates and then
determine positive NPV project, no matter whether shareholders agree

Key concepts

- Derivation of CAPM
- Risk and return under CAPM
- CAPM vs APT
- Application of CAPM
- Empirical properties of CAPM betas
- Empirical tests of CAPM
- CAPM and capital budgeting