Bond Price Volatility

"Well, Beethoven, what is this?"
— Attributed to Prince Anton Esterházy

Price Volatility

- Volatility measures how bond prices respond to interest rate changes.
- It is key to the risk management of interest rate-sensitive securities.

Price Volatility (concluded)

- What is the sensitivity of the percentage price change to changes in interest rates?
- Define price volatility by

$$-\frac{\frac{\partial P}{\partial y}}{P}. \tag{14}$$

Price Volatility of Bonds

- The price volatility of a level-coupon bond is

$$-\frac{(C/y)\,n - \left(C/y^2\right)\left(\left(1+y\right)^{n+1} - (1+y)\right) - nF}{(C/y)\left(\left(1+y\right)^{n+1} - (1+y)\right) + F(1+y)}.$$

  - F is the par value.
  - C is the coupon payment per period.
  - Formula can be simplified a bit with $C = Fc/m$.

  For the above bond,

$$-\frac{\frac{\partial P}{\partial y}}{P} > 0.$$

Macaulay Duration[a]

- The Macaulay duration (MD) is a weighted average of the times to an asset's cash flows.
- The weights are the cash flows' PVs divided by the asset's price.
- Formally,

$$\text{MD} \triangleq \frac{1}{P} \sum_{i=1}^{n} \frac{C_i}{(1+y)^i}\, i.$$

- The Macaulay duration, in periods, is equal to

$$\text{MD} = -(1+y)\, \frac{\partial P}{\partial y} \frac{1}{P}. \tag{15}$$

[a]Macaulay (1938).

MD of Bonds

- The MD of a level-coupon bond is

$$\text{MD} = \frac{1}{P} \left[\sum_{i=1}^{n} \frac{iC}{(1+y)^i} + \frac{nF}{(1+y)^n} \right]. \tag{16}$$

- It can be simplified to

$$\text{MD} = \frac{c(1+y)\left[\,(1+y)^n - 1\,\right] + ny(y-c)}{cy\left[\,(1+y)^n - 1\,\right] + y^2},$$

where c is the period coupon rate.

- The MD of a zero-coupon bond equals n, its term to maturity.
- The MD of a level-coupon bond is less than n.

Remarks

- Equations (15) on p. 93 and (16) on p. 94 hold only if the coupon C, the par value F, and the maturity n are all independent of the yield y.
  - That is, if the cash flow is independent of yields.
- To see this point, suppose the market yield declines.
- The MD will be lengthened.
- But for securities whose maturity actually decreases as a result, the price volatility[a] may decrease.

[a] As originally defined in Eq. (14) on p. 91.

How *Not* To Think about MD

- The MD has its origin in measuring the length of time a bond investment is outstanding.
- But it should be seen mainly as measuring *price volatility*.
- Duration of a security can be longer than its maturity or negative!
- Neither makes sense under the maturity interpretation.
- Many, if not most, duration-related terminology cannot be comprehended otherwise.

Conversion

- For the MD to be year-based, modify Eq. (16) on p. 94 to
$$\frac{1}{P}\left[\sum_{i=1}^{n}\frac{i}{k}\,\frac{C}{\left(1+\frac{y}{k}\right)^{i}}+\frac{n}{k}\,\frac{F}{\left(1+\frac{y}{k}\right)^{n}}\right],$$
where y is the *annual* yield and k is the compounding frequency per annum.

- Equation (15) on p. 93 also becomes
$$\text{MD}=-\left(1+\frac{y}{k}\right)\frac{\partial P}{\partial y}\frac{1}{P}.$$

- By definition, MD (in years) $=\frac{\text{MD (in periods)}}{k}$.

Modified Duration

- Modified duration is defined as

$$\text{modified duration} \stackrel{\Delta}{=} -\frac{\partial P}{\partial y}\frac{1}{P} = \frac{\text{MD}}{(1+y)}. \tag{17}$$

- By the Taylor expansion,

$$\text{percent price change} \approx -\text{modified duration} \times \text{yield change}.$$

Example

- Consider a bond whose modified duration is 11.54 with a yield of 10%.
- If the yield increases instantaneously from 10% to 10.1%, the approximate percentage price change will be

$$-11.54 \times 0.001 = -0.01154 = -1.154\%.$$

Modified Duration of a Portfolio

- The modified duration of a portfolio equals

$$\sum_i \omega_i D_i.$$

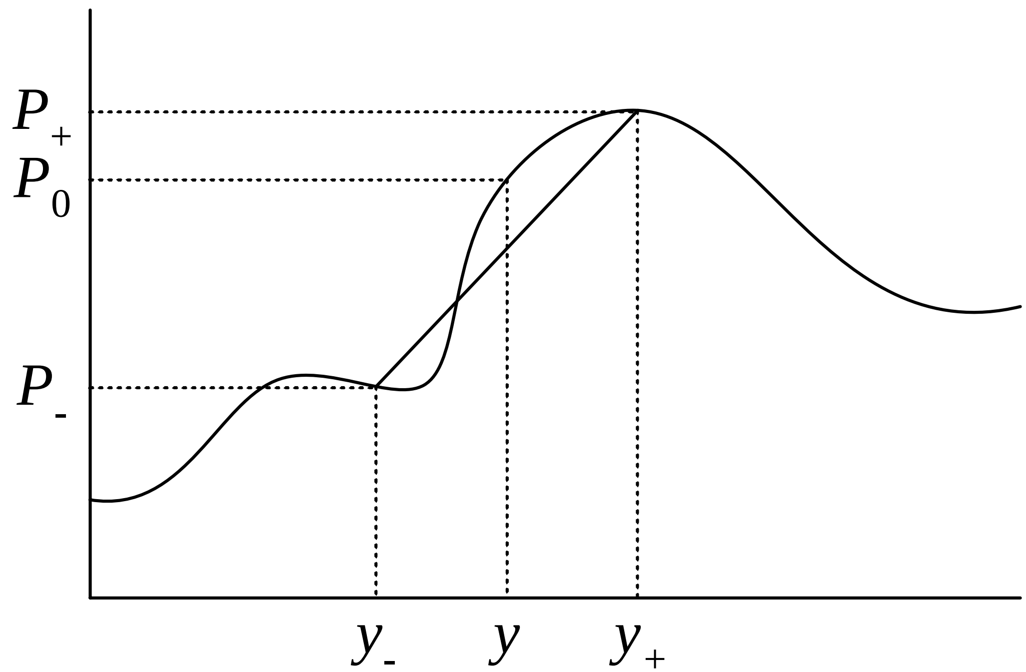
  - D_i is the modified duration of the ith asset.
  - ω_i is the market value of that asset expressed as a percentage of the market value of the portfolio.

Effective Duration

- Yield changes may alter the cash flow or the cash flow may be so complex that simple formulas are unavailable.
- We need a general numerical formula for volatility.
- The effective duration is defined as

$$\frac{P_- - P_+}{P_0(y_+ - y_-)}.$$

  - P_- is the price if the yield is decreased by Δy.
  - P_+ is the price if the yield is increased by Δy.
  - P_0 is the initial price, y is the initial yield.
  - Δy is small.



P+
P0
P-
y-
y
y+

Effective Duration (concluded)

- One can compute the effective duration of just about any financial instrument.
- An alternative is to use

$$\frac{P_0 - P_+}{P_0 \, \Delta y}.$$

  - More economical but theoretically less accurate.

The Practices

- Duration is usually expressed in percentage terms — call it $D_{\%}$ — for quick mental calculation.[a]
- The percentage price change expressed in percentage terms is then approximated by

$$-D_{\%} \times \Delta r$$

  when the yield increases instantaneously by $\Delta r\%$.

  - Price will drop by 20% if $D_{\%} = 10$ and $\Delta r = 2$ because $10 \times 2 = 20$.

- $D_{\%}$ in fact equals modified duration (prove it!).

[a] Neftci (2008), "Market professionals do not like to use decimal points."

Hedging

- Hedging offsets the price fluctuations of the position to be hedged by the hedging instrument in the opposite direction, leaving the total wealth unchanged.
- Define dollar duration as
$$\text{modified duration} \times \text{price} = -\frac{\partial P}{\partial y}.$$
- The approximate *dollar* price change is
$$\text{price change} \approx -\text{dollar duration} \times \text{yield change}.$$
- One can hedge a bond portfolio with a dollar duration D by bonds with a dollar duration $-D$.

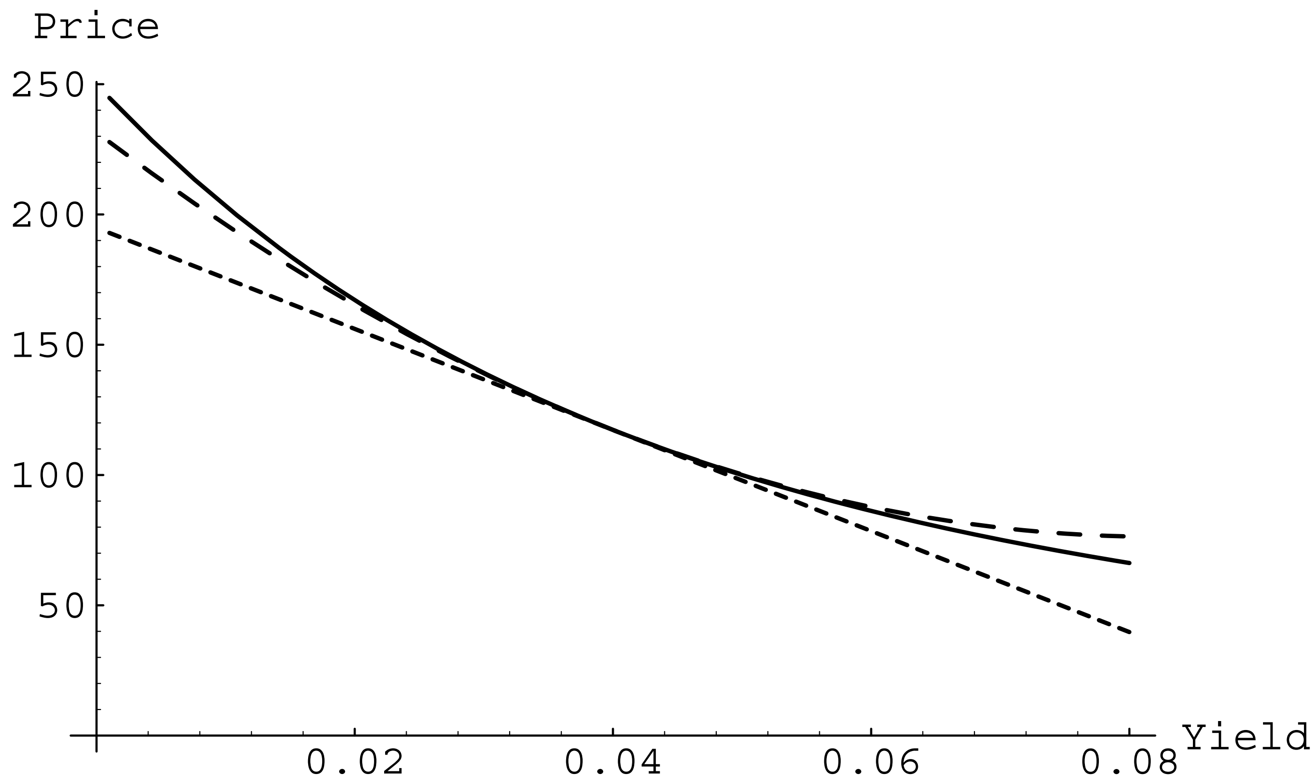
Convexity

- Convexity is defined as

$$\textsf{convexity} \text{ (in periods)} \triangleq \frac{\partial^2 P}{\partial y^2} \frac{1}{P}.$$

- The convexity of a level-coupon bond is positive (prove it!).
- For a bond with positive convexity, the price rises more for a rate decline than it falls for a rate increase of equal magnitude (see plot next page).
- So between two bonds with the same price and duration, the one with a higher convexity is more valuable.[a]

[a]Do you spot a problem here (Christensen & Sørensen, 1994)?


Price
250
200
150
100
50
0.02
0.04
0.06
0.08
Yield

Convexity (concluded)

- Convexity measured in periods and convexity measured in years are related by

$$\text{convexity (in years)} = \frac{\text{convexity (in periods)}}{k^2}$$

when there are k periods per annum.

Use of Convexity

- The approximation $\Delta P/P \approx -$ duration $\times$ yield change works for small yield changes.
- For larger yield changes, use

$$
\begin{aligned}
\frac{\Delta P}{P} &\approx \frac{\partial P}{\partial y}\,\frac{1}{P}\,\Delta y + \frac{1}{2}\,\frac{\partial^2 P}{\partial y^2}\,\frac{1}{P}\,(\Delta y)^2 \\
&= -\text{duration} \times \Delta y + \frac{1}{2} \times \text{convexity} \times (\Delta y)^2.
\end{aligned}
$$

- Recall the figure on p. 107.

The Practices

- Convexity is usually expressed in percentage terms — call it $C_{\%}$ — for quick mental calculation.
- The percentage price change expressed in percentage terms is approximated by

$$-D_{\%} \times \Delta r + C_{\%} \times (\Delta r)^2/2$$

  when the yield increases instantaneously by $\Delta r\%$.

  – Price will drop by 17% if $D_{\%} = 10$, $C_{\%} = 1.5$, and $\Delta r = 2$ because

$$-10 \times 2 + \frac{1}{2} \times 1.5 \times 2^2 = -17.$$

- $C_{\%}$ equals convexity divided by 100 (prove it!).

Effective Convexity

- The effective convexity is defined as

$$\frac{P_+ + P_- - 2P_0}{P_0 \left(0.5 \times (y_+ - y_-)\right)^2},$$

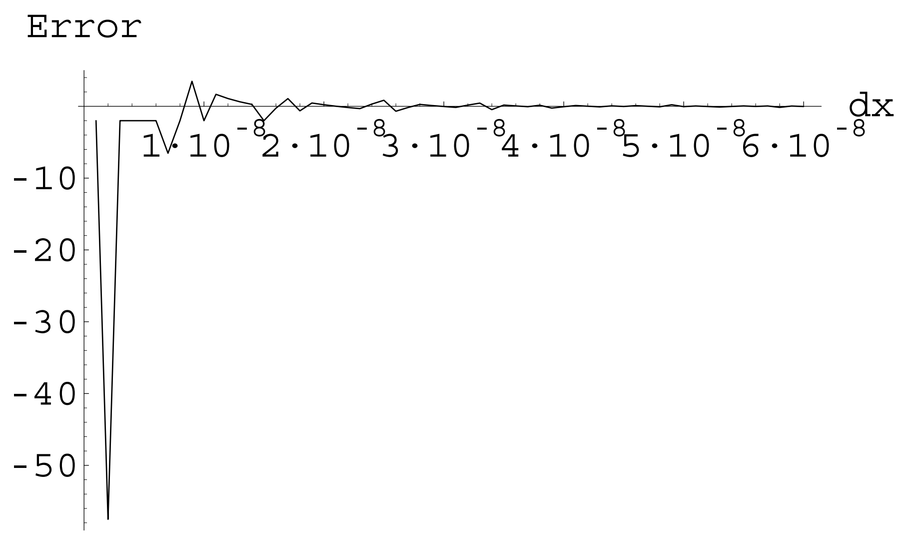
  - P_- is the price if the yield is decreased by Δy.
  - P_+ is the price if the yield is increased by Δy.
  - P_0 is the initial price, y is the initial yield.
  - Δy is small.

- Effective convexity is most relevant when a bond's cash flow is interest rate sensitive.

- Numerically, choosing the right Δy is a delicate matter.

Approximate $d^2 f(x)^2/dx^2$ at $x = 1$, Where $f(x) = x^2$

- The difference of $((1+\Delta x)^2 + (1-\Delta x)^2 - 2)/(\Delta x)^2$ and 2:



- This numerical issue is common in financial engineering but does not admit general solutions yet (see pp. 825ff).

Interest Rates and Bond Prices: Which Determines Which?[a]

- If you have one, you have the other.
- So they are just two names given to the same thing: cost of fund.
- Traders most likely work with prices.
- Banks most likely work with interest rates.

[a] Contributed by Mr. Wang, Cheng (R01741064) on March 5, 2014.

Term Structure of Interest Rates

Why is it that the interest of money is lower,
when money is plentiful?
— Samuel Johnson (1709–1784)

If you have money, don't lend it at interest.
Rather, give [it] to someone
from whom you won't get it back.
— Thomas Gospel 95

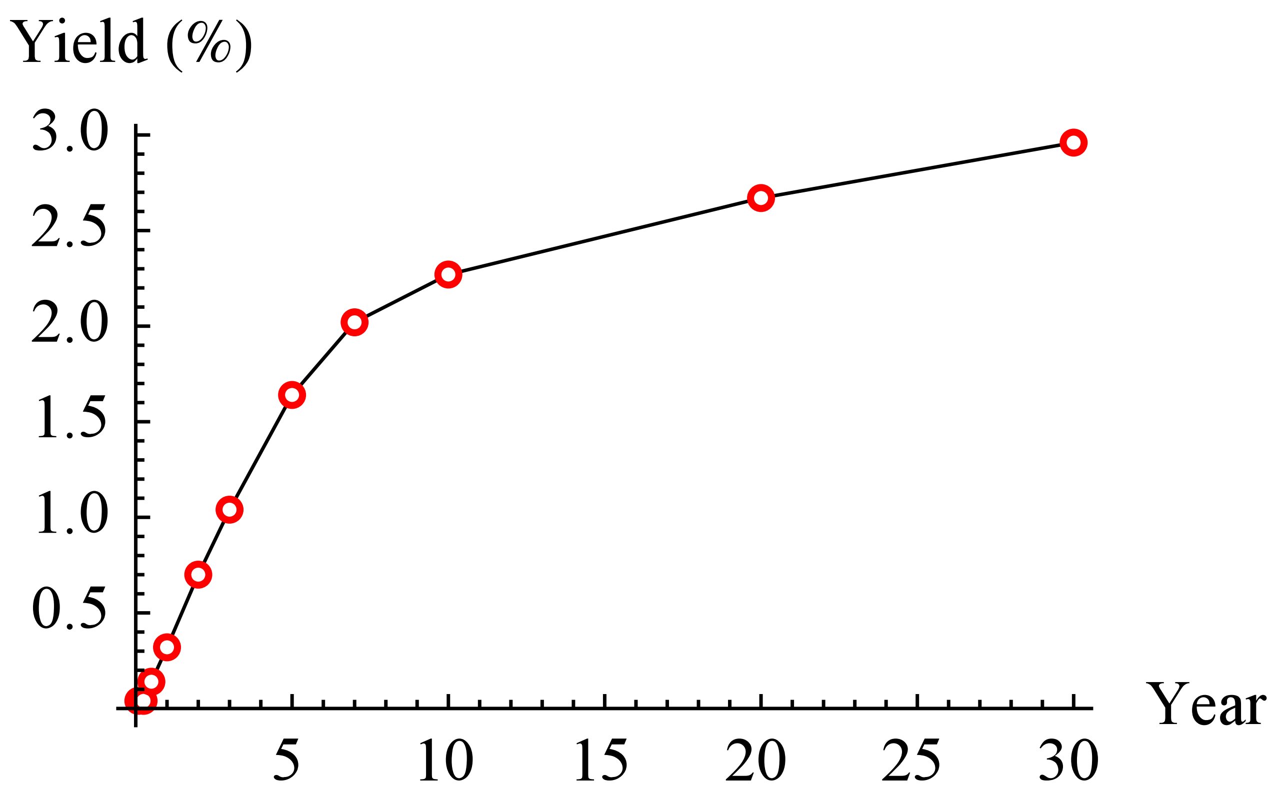
Term Structure of Interest Rates

- Concerned with how interest rates change with maturity.
- The set of yields to maturity for bonds form the term structure.
  - The bonds must be of equal quality.
  - They differ solely in their terms to maturity.
- The term structure is fundamental to the valuation of fixed-income securities.

Term Structure of Interest Rates (concluded)

- Term structure often refers exclusively to the yields of zero-coupon bonds.
- A yield curve plots the yields to maturity of coupon bonds against maturity.
- A par yield curve is constructed from bonds trading near par.

Yield Curve as of July 24, 2015



Four Typical Shapes

- A normal yield curve is upward sloping.
- An inverted yield curve is downward sloping.
- A flat yield curve is flat.
- A humped yield curve is upward sloping at first but then turns downward sloping.

Spot Rates

- The i-period spot rate $S(i)$ is the yield to maturity of an i-period zero-coupon bond.
- The PV of one dollar i periods from now is by definition

$$[\,1 + S(i)\,]^{-i}.$$

  - It is the price of an i-period zero-coupon bond.[a]
- The one-period spot rate is called the short rate.
- Spot rate curve: Plot of spot rates against maturity:

$$S(1), S(2), \ldots, S(n).$$

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[a] Recall Eq. (9) on p. 66.

Problems with the PV Formula

- In the bond price formula (3) on p. 39,

$$\sum_{i=1}^{n} \frac{C}{(1+y)^i} + \frac{F}{(1+y)^n},$$

  every cash flow is discounted at the same yield y.

- Consider two riskless bonds with different yields to maturity because of their different cash flow streams:

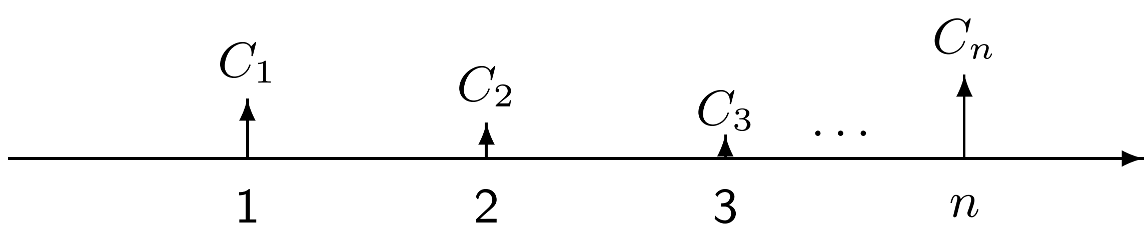
$$\begin{aligned} \text{PV}_1 &= \sum_{i=1}^{n_1} \frac{C}{(1+y_1)^i} + \frac{F}{(1+y_1)^{n_1}}, \\ \text{PV}_2 &= \sum_{i=1}^{n_2} \frac{C}{(1+y_2)^i} + \frac{F}{(1+y_2)^{n_2}}. \end{aligned}$$

Problems with the PV Formula (concluded)

- The yield-to-maturity methodology discounts their *contemporaneous* cash flows with *different* rates.
- But shouldn't they be discounted at the *same* rate?

Spot Rate Discount Methodology

- A cash flow $C_1, C_2, \ldots, C_n$ is equivalent to a package of zero-coupon bonds with the ith bond paying C_i dollars at time i.



Spot Rate Discount Methodology (concluded)

- So a level-coupon bond has the price

$$P = \sum_{i=1}^{n} \frac{C}{[\,1 + S(i)\,]^i} + \frac{F}{[\,1 + S(n)\,]^n}. \tag{18}$$

- This pricing method incorporates information from the term structure.
- It discounts each cash flow at the corresponding spot rate.

Discount Factors

- In general, any riskless security having a cash flow $C_1, C_2, \ldots, C_n$ should have a market price of

$$P = \sum_{i=1}^{n} C_i d(i).$$

  - Above, $d(i) \stackrel{\Delta}{=} [\,1 + S(i)\,]^{-i}$, $i = 1, 2, \ldots, n$, are called the discount factors.
  - $d(i)$ is the PV of one dollar i periods from now.
  - This formula—now just a definition—will be justified on p. 215.
- The discount factors are often interpolated to form a continuous function called the discount function.

Extracting Spot Rates from Yield Curve

- Start with the short rate $S(1)$.
  - Note that short-term Treasuries are zero-coupon bonds.
- Compute $S(2)$ from the two-period coupon bond price P by solving

$$P = \frac{C}{1 + S(1)} + \frac{C + 100}{[\,1 + S(2)\,]^2}.$$

Extracting Spot Rates from Yield Curve (concluded)

- Inductively, we are given the market price P of the n-period coupon bond and

$$S(1), S(2), \dots, S(n-1).$$

- Then $S(n)$ can be computed from Eq. (18) on p. 124, repeated below,

$$P = \sum_{i=1}^{n} \frac{C}{[\,1 + S(i)\,]^i} + \frac{F}{[\,1 + S(n)\,]^n}.$$

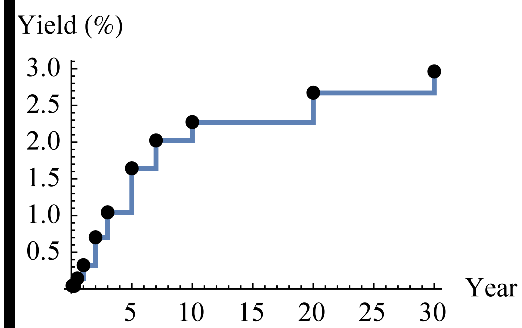
- The running time can be made to be $O(n)$ (see text).
- The procedure is called bootstrapping.

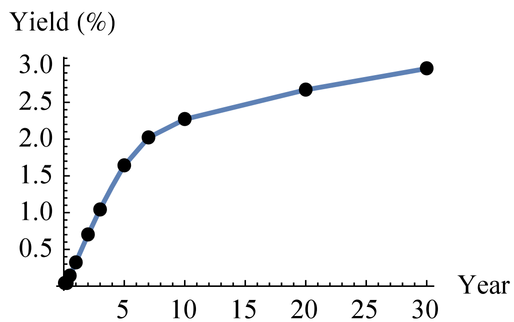
Some Problems

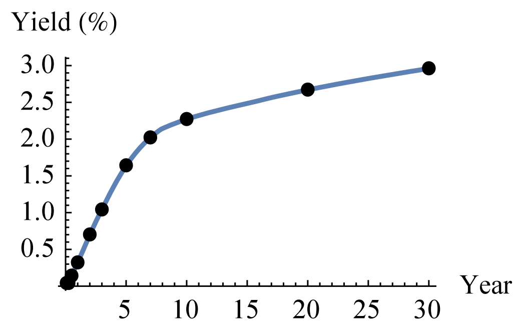
- Treasuries of the same maturity might be selling at different yields (the multiple cash flow problem).
- Some maturities might be missing from the data points (the incompleteness problem).
- Treasuries might not be of the same quality.
- Interpolation and fitting techniques are needed in practice to create a smooth spot rate curve.[a]

[a] Often without economic justifications.

Which One?


Yield (%)
3.0
2.5
2.0
1.5
1.0
0.5
5
10
15
20
25
30
Year


Yield (%)
3.0
2.5
2.0
1.5
1.0
0.5
5
10
15
20
25
30
Year


Yield (%)
3.0
2.5
2.0
1.5
1.0
0.5
5
10
15
20
25
30
Year

Yield Spread

- Consider a *risky* bond with the cash flow $C_1, C_2, \ldots, C_n$ and selling for P.
- Calculate the IRR of the risky bond.
- Calculate the IRR of a riskless bond with comparable maturity.
- Yield spread is their difference.

Static Spread

- Were the risky bond riskless, it would fetch

$$P^* = \sum_{t=1}^{n} \frac{C_t}{[\,1 + S(t)\,]^t}.$$

- But as risk must be compensated, in reality $P < P^*$.
- The static spread is the amount s by which the spot rate curve has to shift *in parallel* to price the risky bond:

$$P = \sum_{t=1}^{n} \frac{C_t}{[\,1 + s + S(t)\,]^t}.$$

- Unlike the yield spread, the static spread incorporates information from the term structure.

Of Spot Rate Curve and Yield Curve

- y_k: yield to maturity for the k-period coupon bond.
- $S(k) \geq y_k$ if $y_1 < y_2 < \cdots$ (yield curve is normal).
- $S(k) \leq y_k$ if $y_1 > y_2 > \cdots$ (yield curve is inverted).
- $S(k) \geq y_k$ if $S(1) < S(2) < \cdots$ (spot rate curve is normal).
- $S(k) \leq y_k$ if $S(1) > S(2) > \cdots$ (spot rate curve is inverted).
- If the yield curve is flat, the spot rate curve coincides with the yield curve.

Shapes

- The spot rate curve often has the same shape as the yield curve.
  - If the spot rate curve is inverted (normal, resp.), then the yield curve is inverted (normal, resp.).
- But this is only a trend not a mathematical truth.[a]

[a] See a counterexample in the text.

Forward Rates

- The yield curve contains information regarding future interest rates currently "expected" by the market.
- Invest \$1 for j periods to end up with $[\,1+S(j)\,]^j$ dollars at time j.
  - The maturity strategy.
- Invest \$1 in bonds for i periods and at time i invest the proceeds in bonds for another $j-i$ periods where $j>i$.
- Will have $[\,1+S(i)\,]^i[\,1+S(i,j)\,]^{j-i}$ dollars at time j.
  - $S(i,j)$: $(j-i)$-period spot rate i periods from now.
  - The rollover strategy.

Forward Rates (concluded)

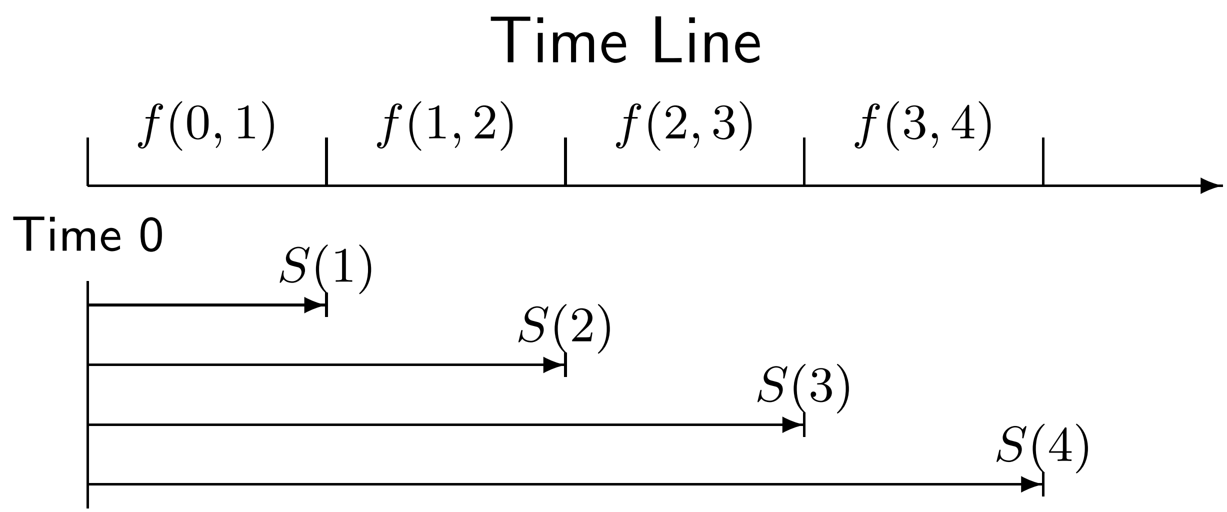
- When $S(i,j)$ equals

$$f(i,j) \stackrel{\Delta}{=} \left[\frac{(1+S(j))^j}{(1+S(i))^i} \right]^{1/(j-i)} - 1, \tag{19}$$

  we will end up with $[\,1+S(j)\,]^j$ dollars again.

- By definition, $f(0,j) = S(j)$.

- $f(i,j)$ is called the (implied) forward rates.
  - More precisely, the $(j-i)$-period forward rate i periods from now.


Time Line
f(0, 1)
f(1, 2)
f(2, 3)
f(3, 4)
Time 0
S(1)
S(2)
S(3)
S(4)

Forward Rates and Future Spot Rates

- We did not assume any a priori relation between $f(i, j)$ and future spot rate $S(i, j)$.
  - This is the subject of the term structure theories.
- We merely looked for the future spot rate that, *if realized*, will equate the two investment strategies.
- $f(i, i+1)$ are called the instantaneous forward rates or one-period forward rates.

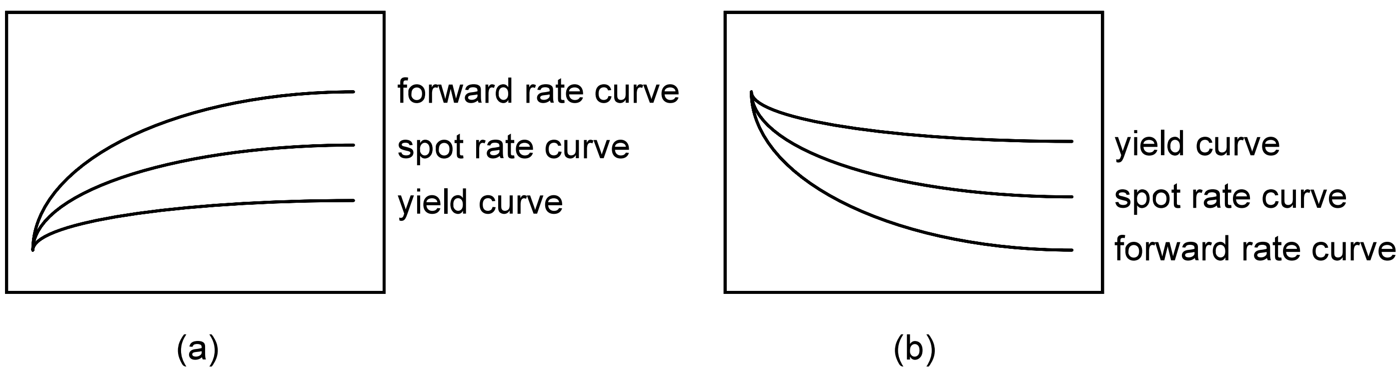
Spot Rates and Forward Rates

- When the spot rate curve is normal, the forward rate dominates the spot rates,

$$f(i,j) > S(j) > \cdots > S(i).$$

- When the spot rate curve is inverted, the forward rate is dominated by the spot rates,

$$f(i,j) < S(j) < \cdots < S(i).$$


forward rate curve
spot rate curve
yield curve
(a)
yield curve
spot rate curve
forward rate curve
(b)

Forward Rates $\equiv$ Spot Rates $\equiv$ Yield Curve

- The FV of \$1 at time n can be derived in two ways.
- Buy n-period zero-coupon bonds and receive

$$[\,1 + S(n)\,]^n.$$

- Buy one-period zero-coupon bonds today and a series of such bonds at the forward rates as they mature.
- The FV is

$$[\,1 + S(1)\,][\,1 + f(1,2)\,]\cdots[\,1 + f(n-1,n)\,].$$

Forward Rates ≡ Spot Rates ≡ Yield Curves (concluded)

- Since they are identical,

$$S(n) = \{[\,1 + S(1)\,][\,1 + f(1,2)\,] \cdots [\,1 + f(n-1,n)\,]\}^{1/n} - 1. \tag{20}$$

- Hence, the forward rates (specifically the one-period forward rates) determine the spot rate curve.
- Other equivalencies can be derived similarly, such as

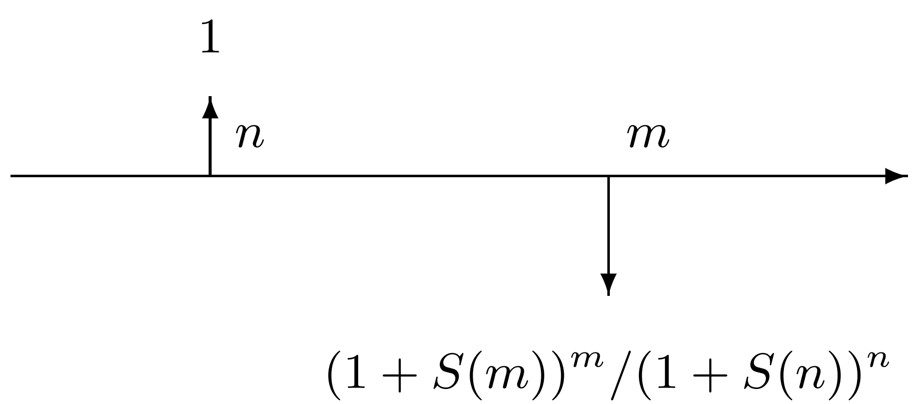
$$f(T, T+1) = \frac{d(T)}{d(T+1)} - 1. \tag{21}$$

Locking in the Forward Rate $f(n, m)$

- Buy one n-period zero-coupon bond for $1/(1+S(n))^n$ dollars.
- Sell $(1+S(m))^m/(1+S(n))^n$ m-period zero-coupon bonds.
- No net initial investment because the cash inflow equals the cash outflow: $1/(1+S(n))^n$.
- At time n there will be a cash inflow of \$1.
- At time m there will be a cash outflow of $(1+S(m))^m/(1+S(n))^n$ dollars.

Locking in the Forward Rate $f(n, m)$ (concluded)

- This implies the rate $f(n, m)$ between times n and m.



Forward Loans

- We had generated the cash flow of a type of forward contract called the forward loan.
- Agreed upon today, it enables one to
  - Borrow money at time n in the future, and
  - Repay the loan at time $m > n$ with an interest rate equal to the forward rate

$$f(n, m).$$

- Can the spot rate curve be an arbitrary curve?[a]

[a] Contributed by Mr. Dai, Tian-Shyr (B82506025, R86526008, D88526006) in 1998.

Synthetic Bonds

- We had seen that

$$\begin{aligned} & \text{forward loan} \\ = \quad & n\text{-period zero} - [\,1 + f(n, m)\,]^{m-n} \times m\text{-period zero}. \end{aligned}$$

- Thus

$$\begin{aligned} & n\text{-period zero} \\ = \quad & \text{forward loan} + [\,1 + f(n, m)\,]^{m-n} \times m\text{-period zero}. \end{aligned}$$

- We have created a *synthetic* zero-coupon bond with forward loans and other zero-coupon bonds.
- Very useful if the n-period zero is unavailable or illiquid.