

**"CONTROLLING THE INTEREST-RATE RISK OF
BONDS: AN INTRODUCTION TO DURATION
ANALYSIS AND IMMUNIZATION STRATEGIES"**

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N° 87 / 28

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Director of Publication :

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for Research and Development

Printed at INSEAD,
Fontainebleau, France

CONTROLLING THE INTEREST-RATE RISK OF BONDS:
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AND IMMUNIZATION STRATEGIES

(Forthcoming in Financial Markets and Portfolio Management)

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September 1987

* An earlier version of this article was written for the first European Portfolio Investment Colloquium in Fontainebleau (1985). The article was rewritten while the author was a visiting professor at the Wharton School of the University of Pennsylvania (Philadelphia). The author thanks Jean Dermine and Harold Bierman for their useful comments and Gillian Hay for typing several versions of the manuscript.

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AND IMMUNIZATION STRATEGIES

In this article we introduce the concept of duration as a measure of interest-rate risk exposure. We then show how duration can be used to design a strategy to protect (or immunize) an asset's value from unanticipated changes in the level of interest rates.

Nous présentons dans cet article la notion de "duration" qui s'interprète comme une mesure du risque de taux d'intérêt. On montre ensuite comment on peut utiliser la "duration" d'un actif pour mettre en oeuvre une stratégie qui protège (ou immunise) cet actif contre les fluctuations non-anticipées des taux d'intérêts.

CONTROLLING THE INTEREST-RATE RISK OF BONDS:
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1. Introduction

Consider a bond with an annual coupon-rate of 8 percent and a 6-year term to maturity. Suppose that the prevailing market yield (or level of interest rate) is also 8 percent. The bond sells at par since its coupon rate is equal to the prevailing market yield.

Assume that there is an unanticipated increase in the market yield from 8 percent to 8½ percent. The bond's price must drop to reflect the rise in the level of the market yield. The bond is now selling at a discount from face value. Its price is 97.72¹. At this price it yields 8½ percent. In percentage terms, the drop in price is equal to 2.28 percent $[(97.72 - 100)/100]$. Had the market yield gone down from 8 percent to 7½ percent, the price of the bond would have gone up from 100 to 102.35, an increase in price of 2.35 percent².

The above numerical example illustrates a straight forward phenomenon regarding bonds. Their price fluctuates unexpectedly in response to unanticipated changes in the market yield. In other words, bonds are exposed to interest-rate risk. This source of risk differs from so-called creditor or default risk. The former originates in the market and affects all bonds. The latter is issuer-specific. It refers to the probability that the issuer will not service his debt according to the agreed-upon schedule, the extreme case being default.

In what follows we only examine interest-rate risk. We want to answer two questions. How can we measure a bond's exposure to interest-rate risk? And how can we protect a bond's value from unanticipated rises and declines in the level of interest rates?

We will see that duration, a major characteristic of bonds, provides an answer to both questions. In section 2 we show that a bond's duration is a convenient measure of its exposure to interest-rate risk and in sections 4 and 5 we demonstrate that if a bond is held over a period of time equal to its duration then its return over the holding period is

unaffected by changes in interest rates. The bond is said to be immunized against interest-rate risk. To illustrate, suppose that you bought the 6-year, 8-percent bond selling at par. In section 6 we show that the duration of this bond is equal to 5 years. Hence, if you hold the bond over a 5-year period, you should earn 8 percent even if the level of interest rate changes after you purchased the bond³.

2. A bond's duration is a measure of its exposure to interest-rate risk

We have already seen that when the market rate increases from 8 percent to 8½ percent, the price of the 6-year, 8-percent-annual-coupon bond drops by 2.28 percent. This percentage drop in price - which is a measure of the bond's exposure to interest-rate risk - can be calculated indirectly if we know the bond's duration. It is given by the following relationship⁴:

$$\left(\begin{array}{c} \text{percentage change} \\ \text{in bond price} \end{array} \right) = - (\text{duration}) \left(\frac{\text{change in market yield}}{1 + \text{market yield}} \right).$$

The ratio $\left(\frac{\text{duration}}{1 + \text{market yield}} \right)$ is usually referred to as "modified"

duration. For example, at the prevailing 8-percent market yield, a bond with a 5-year duration has a 4.62-year modified duration (5 divided by 1.080). If we use the symbol $\Delta P/P$ to express the percentage change in bond price, MD to express modified duration and Δy to express the change in market yield then the above relationship can be symbolically rewritten as:

$$\frac{\Delta P}{P} = - (MD) \cdot (\Delta y) \quad .$$

This equation indicates that, given an absolute change in market yield (Δy), a bond's percentage change in price is proportional to its modified duration. Hence modified duration (or duration) is a measure of a bond's price sensitivity to changes in interest-rates. In other words, it is a measure of the bond's exposure to interest-rate risk. It also follows from the above relationship that the longer a bond's duration, the higher its exposure to interest-rate risk.

We will show in section 6 that the duration of the 6-year, 8-percent bond is equal to 5 years. At a market yield of 8 percent, modified duration is equal to 4.62 years. If the market yield increases from 8 percent to 8.50 percent ($\Delta y = .005$) the corresponding percentage change in price is:

$$\frac{\Delta P}{P} = -(4.62)(.005) = -2.31 \text{ percent} \quad .$$

In words, if the market yield increases by 50 basis points (from 8 percent to 8.50 percent) then the associated drop in the price of the bond should be equal to 2.31 percent.

It is important to note that the relationship between percentage price change and duration works approximately. Indeed, we know that the exact drop in price is 2.28 percent rather than the 2.31 percent given by the formula. When the market yield increases the duration formula overestimates the percentage drop in price. The opposite is true when the market yield decreases. In this case the duration formula underestimates the percentage increase in price (if the yield drops to 7.50 percent, the exact percentage increase in the bond's price is 2.35 percent rather than the 2.31 percent given by the formula). Anyway, the accuracy of the formula improves the smaller the change in yield. For infinitely small changes in yield the formula is exact. But for large increases (say 2 percentage points), the formula gives a poor estimate of the percentage change in price. This phenomenon is illustrated in Exhibit 1. The third column gives the exact percentage change in price and the fourth column gives the percentage change in price calculated with the duration formula. We can see that for a very small change in yield of one basis point (from 8 percent to either 8.01 percent or 7.99 percent), the exact and the calculated percentage changes in price are practically the same (.0462%). But for a very large change in yield of 200 basis points (from 8 percent to either 6 percent or 10 percent), there is a wide difference between the exact and the calculated percentage changes in price. For example an increase in yield from 8 percent to 10 percent reduces price by about 8.71 percent rather than the 9.24 percent given by the formula.

EXHIBIT 1

MEASURING CHANGES IN BOND PRICES WITH DURATION

Consider a 6-year 8-percent-annual-coupon bond selling at par (1000) when the market yield is 8 percent. Assume several changes in market yield as shown in the first column. The second column gives the corresponding price. The third column indicates the exact percentage price change from a base price of 1000. The fourth column gives the percentage price change calculated according to the duration formula¹. The last column gives the error in basis points resulting from using the duration formula (column 3 minus column 4).

Market Rate (y)	Corresponding Price P(y)	$\frac{\Delta P}{P} = \frac{P(y)-1000}{1000}$	$\frac{\Delta P}{P} = -MD \cdot \Delta y$	Error in basis points
10.00%	912.89479	-8.710521%	-9.245741%	53.5220
8.50%	977.23206	-2.276794%	-2.311435%	3.4641
8.01%	999.53785	-0.046215%	-0.046229%	0.0014
8.00%	1000.00000			
7.99%	1000.46243	+0.046243%	+0.046229%	0.0014
7.50%	1023.46923	+2.346923%	+2.311435%	3.5488
6.00%	1098.34649	+9.834649%	+9.245741%	58.8908

¹. In the duration formula we use the exact value of the bond's duration which is 4.9927 years rather than 5 years. See section 6 on how to calculate duration.

The duration formula doesn't provide exact percentage price changes because it assumes a linear relationship between price changes and yield changes whereas the exact relationship between bond prices and yields is actually convex. The reader will find a discussion on bond convexity and its relationship to bond duration in Appendix One where we give a formula to calculate a bond's exposure to interest-rate risk when the change in yield is relatively large.

3. A bond's duration can be used to modify its exposure to interest-rate risk

Suppose that you wish to reduce the interest-rate risk exposure of a bond (or a portfolio of bonds). You can achieve this by shortening the duration of the bond (or a portfolio of bonds). If you wish to increase interest-rate risk exposure you would do the opposite: you would lengthen the duration of the bond (or a portfolio of bonds).

In order to modify the duration of a portfolio of bonds you must rebalance the portfolio. For example, to reduce duration you sell bonds with relatively long duration and purchase bonds with relatively short duration in such a way as to achieve a desired shorter duration for the portfolio. This will be illustrated in sections 9 and 10. And to modify the duration of a single bond, you must combine it with another bond (or another financial instrument) with a shorter or longer duration. This will be illustrated in section 9.

4. A bond's duration is equal to its "immunized" holding period

As pointed out earlier, if the bond is held over a period of 5 years (a length of time equal to its duration) then the bondholder is immunized against a change in the level of the rate of interest. In other words, the holder of the bond is assured a realized return of 8 percent (the bond's original yield to maturity) even though the rate of interest may change immediately after the bond is purchased.

It is important to note, however, that this immunization strategy will work only if the yield curve is flat (i.e., the yield on all bonds is the same regardless of their term to maturity) and changes in the market yield are the same for all bonds (i.e., that the flat yield curve moves in

a parallel fashion). We will refer to this strategy as "conventional" immunization strategy. In Appendix Two we examine what happens when the conditions for conventional immunization are not met. It should also be pointed out that the 6-year, 8-percent coupon bond is immunized against a change in the rate of interest that occurs immediately after the bond is purchased. We will see that as time passes, the bond's duration will no longer be equal to the remainder of the 5-year holding period and hence the bond will no longer be immunized. Continuous immunization will require "portfolio" rebalancing. This point is explained and illustrated in section 10.

5. How does conventional immunization work ?

In order to understand how immunization works we must understand how an unanticipated change in the rate of interest affects the profitability of an investment in a bond (or a portfolio of bonds).

First, a change in the interest rate affects the price of the bond (or the value of the portfolio). An increase in the interest rate creates a capital loss and a decrease in the interest rate creates a capital gain because the price of the bond (or the value of the portfolio) must adjust downward or upward to reflect the new rate of interest prevailing in the market. This is the price risk.

Second, a change in the interest rate affects the future income from the reinvestment of the bond's (or portfolio) coupon payments. An increase in the interest rate means that future coupon payments can be reinvested at a higher rate thus creating additional income. A decrease in the interest rate means that future coupon payments will be reinvested at a lower rate thus creating a loss of income. This is the reinvestment risk.

The interesting aspect of this phenomenon is that the two types of risk work in opposite directions. An increase in interest rate creates a capital loss but generates higher income from coupon reinvestment. A decrease in interest rate creates a capital gain but reduces the income from coupon reinvestment. The bond (or portfolio of bonds) has a "built-in" hedge against interest-rate fluctuations. The important point is that if the bond is held over a period of time equal to its duration the two types of risk offset each other completely and the bond is perfectly

EXHIBIT 2

IMMUNIZATION: A NUMERICAL ILLUSTRATION

Consider a 6-year, 8-percent-annual-coupon bond selling at par (1,000). Its duration is equal to 5 years. Assume holding periods of 6, 5 and 4 years. The market rate either declines by 1% or rises by 1%. What is the realized compounded annual return on holding the bond over the three holding periods ?

<u>Market rate</u>	<u>Initial yield</u>	<u>Market rate drops to 1%</u>	<u>Market rate rises to 1%</u>
	8%	7%	9%
<u>CASE 1: 6-YEAR HOLDING PERIOD</u>			
Bond price after 6 years	1,000	1,000	1,000
Coupon payments (6 x 80)	480	480	480
Reinvestment income ¹	107	92	122
	-----	-----	-----
Total terminal value	1,587	1,572	1,602
Initial investment	1,000	1,000	1,000
Realized compounded annual return ²	8%	7.83%	8.17%
<u>CASE 2: 5-YEAR HOLDING PERIOD</u>			
Bond price after 5 years ³	1,000	1,009	991
Coupons payment (5 x 80)	400	400	400
Reinvestment income	69	60	78
	-----	-----	-----
Total terminal value	1,469	1,469	1,469
Initial investment	1,000	1,000	1,000
Realized compounded annual return	8%	8%	8%
<u>CASE 3: 4-YEAR HOLDING PERIOD</u>			
Bond price after 4 years ³	1,000	1,018	982
Coupons payment (4 x 80)	320	320	320
Reinvestment income	41	35	46
	-----	-----	-----
Total terminal value	1,361	1,373	1,348
Initial investment	1,000	1,000	1,000
Realized compounded annual return	8%	8.25%	7.75%

¹. Reinvestment income = (Terminal value of the reinvested coupon stream at the market rate) - (Sum of the coupon payments). For example, at 8%, the 6-year stream of coupon payments is an annuity whose terminal value is $80 \times 7.336 = 587$. Subtracting from this the sum of the coupon payments (6x80) we obtain 107.

². Realized compounded return = $\sqrt[n]{\text{Terminal value}/\text{Initial investment}} - 1$

³. Bond price = Present value of the bond at the market rate one year before maturity (case 2) and two years before maturity (case 3).

hedged against interest-rate risk over a horizon equal to its duration. The bond is said to be immunized against interest-rate risk.

The principle of immunization can be illustrated numerically with the 6-year, 8-percent-annual-coupon bond selling at par⁵. Its duration, is equal to 5 years (see section 6 and Exhibit 3). This means that if the bond is held for 5 years it will be immunized against interest-rate risk. The realized return will be 8 percent regardless of the change in interest rate following the purchase of the bond. This result is illustrated in Exhibit 2. The column before the last indicates the realized return if the market rate declines by 1 percent from 8 percent to 7 percent. The last column indicates the realized return if the market rate rises by 1 percent from 8 percent to 9 percent. These realized returns are calculated for 3 cases. In the first case, the bond is held to maturity (6 years). In this case the price risk is eliminated. Only the reinvestment risk remains and hence, the realized return drops to 7.83 percent when the market rate declines by 1 percent and rises to 8.17 percent when the market rate rises by 1 percent reflecting the effect of coupon reinvestment below and above 8 percent. In the second case, the bond is held for 5 years, a horizon equal to its duration. Here, the realized return is 8 percent regardless of the change in the market rate. Price risk and reinvestment risk exactly offset each other and the realized return is always equal to the initial expected return of 8 percent. The bond is immunized. In the third case, the bond is held over a horizon shorter than its duration (4-year holding period). Here, the realized return exceeds 8 percent when the market rate declines and falls short of 8 percent when the market rate rises. The bond is not immunized against interest-rate risk since the holding period differs from the bond's duration.

6. How to calculate duration

Suppose that you will receive 100 in one year and 200 in two years. Define the maturity of a given cash-flow as the length of time from now to the date at which that cash-flow will be received. In our example 100 has a one-year-maturity and 200 has a two-year maturity. The duration of this cash-flow stream is defined as the value-weighted average of the maturities of the cash-flows where the weight of a particular cash-flow is the ratio of the present value of that cash-flow to the present value of the whole cash-flow stream. If the market yield is 10 percent, the first

cash-flow has a present value of $100 \times .9091 = 90.91$ and the second cash-flow a present value of $100 \times .8264 = 165.28$. The whole cash-flow stream has a present value of 90.91 plus 165.28 which is equal 256.19 and the duration of the cash-flow stream is⁶:

$$D = \frac{90.91}{256.19} (1) + \frac{165.28}{256.19} (2) = 1.65$$

$$D = (35.48\%)(1) + (64.52\%)(2) = 1.65 \quad .$$

The first cash-flow has a 35.48 percent weight and the second cash-flow a 64.54 percent weight. As a result the "average maturity" of the whole cash-flow is only 1.65 years. It is shorter than the 2-year maturity of the terminal cash flow.

The upper part of Exhibit 3 gives the general formula to calculate the duration of any cash-flow stream. It can be applied to the case of a bond. Consider the 6-year, 8-percent-coupon bond selling at par. Its duration is calculated in the lower part of Exhibit 3. It is equal to 5 years. Note that the bond's duration is shorter than its term to maturity. The relationship between a bond's duration and its term to maturity is examined in section 8.

One problem with calculating duration with the formula given in Exhibit 3 is that it requires many computational steps and more so the longer the bond's term to maturity. This problem can be overcome with the use of several short-cut formulas listed in Exhibit 4⁷.

Formula (1) gives the duration of a standard bond, formula (2) the duration of a bond selling at par, formula (3) the duration of a zero-coupon bond, formula (4) the duration of a perpetual bond and formula (5) the duration of an annuity or equal payment bond.

Recall our 6-year, 8-percent bond selling at par. We can verify that its duration is indeed 5 years. According to formula (2) in Exhibit 4 we have:

$$D = (1 + .08)(4.6229) = 4.9927 \text{ years} \approx 5 \text{ years} \quad .$$

EXHIBIT 3

HOW TO CALCULATE THE DURATION OF A CASH FLOW STREAM

Consider the following notation:

D = duration of a cash flow stream

CF_t = Cash flow received at the end of period t

n = period at which the last cash flow is received

DF_t = discount factor at the rate y for t periods = $\frac{1}{(1 + y)^t}$

$\sum_{t=1}^n$ = sum of the terms from t equal 1 to t equal n

Given the above, the general formula to calculate duration of any cash-flow stream is:

$$D = \frac{\sum_{t=1}^n (CF_t)(DF_t)(t)}{\sum_{t=1}^n (CF_t)(DF_t)}$$

Numerical illustration: What is the duration of a 6-year, 8-percent-annual-coupon bond selling at par (n=6 and y=.08) ?

t	CF_t	DF_t	$CF_t \cdot DF_t$	$CF_t \cdot DF_t \cdot t$
1	80	.9259	74.07	74.07
2	80	.8573	68.59	137.18
3	80	.7938	63.51	190.53
4	80	.7350	58.80	235.20
5	80	.6806	54.45	272.25
6	1080	.6302	680.58	4083.48
			1000.00	4992.71

$$D = \frac{4992.71}{1000.00} = 4.99271 \text{ years} \approx 5 \text{ years}$$

EXHIBIT 4

FORMULAS TO CALCULATE THE DURATION OF BONDS¹

SYMBOLS	{	D = duration
		y = the bond's yield to maturity (market yield)
		c = the bond's coupon rate
		n = the bond's term to maturity
		DF= the discount factor at the rate y for n periods = $\frac{1}{(1+y)^n}$
		ADF= the annuity discount factor = $\frac{1 - DF}{y}$

(1) STANDARD BOND (GENERAL CASE)	$D = \frac{(1+y)c(ADF) + n(y-c)(DF)}{c + (y-c)DF}$
(2) STANDARD BOND SELLING AT PAR ²	$D = (1+y)(ADF)$
(3) ZERO-COUPON BOND ³	$D = n$
(4) PERPETUAL BOND ⁴	$D = 1 + \frac{1}{y}$
(5) EQUAL-PAYMENT BOND (ANNUITY)	$D = \frac{(1+y)(ADF) - n(DF)}{1 - DF}$

1. Assuming a flat yield curve (all bonds have the same yield).
2. This is a special case of formula (1) in which y=c (bond selling at par).
3. This is a special case of formula (1) in which c=0 (zero-coupon bond).
4. This is a special case of formula (1) in which DF=0 and ADF= $\frac{1}{y}$ (perpetual bond).

What is that bond's duration if the market yield is 10 percent rather than 8 percent? Note that at 10 percent the bond sells at a discount. Hence its duration is given by formula (1):

$$D = \frac{(1 + .10).08(4.3553) + 6(.02)(.5645)}{.08 + (.02)(.5645)} = 4.94 \text{ years.}$$

An increase in yield, other things the same, shortens a bond's duration. When the level of interest rates is relatively high, the duration of bonds are relatively short. In other words, a bond's interest-rate risk exposure is relatively lower when the level of interest rates is relatively high. We will return to this point in section 8.

Suppose that a bond has no intermediate coupon payments, i.e., it is a zero-coupon bond. In this case the bond's duration equals its term to maturity. The bond's duration is equal to 6 years since its term to maturity is 6 years. We will see below that only coupon-bearing bonds have a duration shorter than their term to maturity. Note that a lowering of a bond's coupon-rate lengthens its duration. The 6-year, 8-percent-coupon bond has a duration of 5 years. But the 6-year zero-coupon bond has a duration of 6-years.

Consider a perpetual bond. Its duration is given by formula (4). At a market yield of 8 percent it is equal to:

$$D = 1 + \frac{1}{.08} = 13.5 \text{ years.}$$

Note that a lengthening of the time to maturity lengthens duration and that the duration of a perpetual bond is independent of its coupon rate. It is only a function of the market yield. We have already pointed out that duration shortens when the market yield rises. At a yield of 8 percent the duration of a perpetual bond is 13.5 years. But at a yield of 20 percent its duration is only 6 years. Hence, when interest rates are relatively high (say in the neighborhood of 20 percent) it is not possible to find coupon-bearing bonds with duration exceeding 6 years. This phenomenon explains the demand for zero-coupon bond when interest rates are relatively high. It is the only way to obtain debt instruments with relatively long durations.

Finally, consider a 6-year equal-payment bond (a 6-year annuity). Its duration is given by formula (5). At a market yield of 8 percent it is equal to:

$$D = \frac{(1.08)(4.623) - 6(.630)}{1 - .630} = 3.29 \text{ years.}$$

As in the case of a perpetual bond, the duration of an equal-payment bond is independent of its coupon rate. It is only a function of the market yield and the term to maturity. Note that the equal-payment bond has a shorter duration than the standard bond.⁸

7. Why is the duration of a coupon-bearing bond shorter than its maturity?

A duration shorter than maturity reflects the fact that bondholders will get cash inflows (in the form of coupon payments) long before the bond matures. As a matter of fact, the faster bondholders recover part of their initial investment (via coupon payments) the shorter the bond's duration relative to its maturity. Hence, duration is a measure of a bond's value-weighted average maturity, i.e., a measure of its "longness" that takes into account both the timing and the size of the bond's future cash inflows.

If the bond does not have any intermediate coupon payments (a zero-coupon bond) its duration equals its maturity. In this case, the bond's value-weighted maturity is equal to the bond's term to maturity. If the bond has relatively large intermediate payments (the extreme case is that of the equal-payment bond) its duration will be shorter than its maturity.

8. What are the determinants of duration and the exposure to interest-rate risk ?

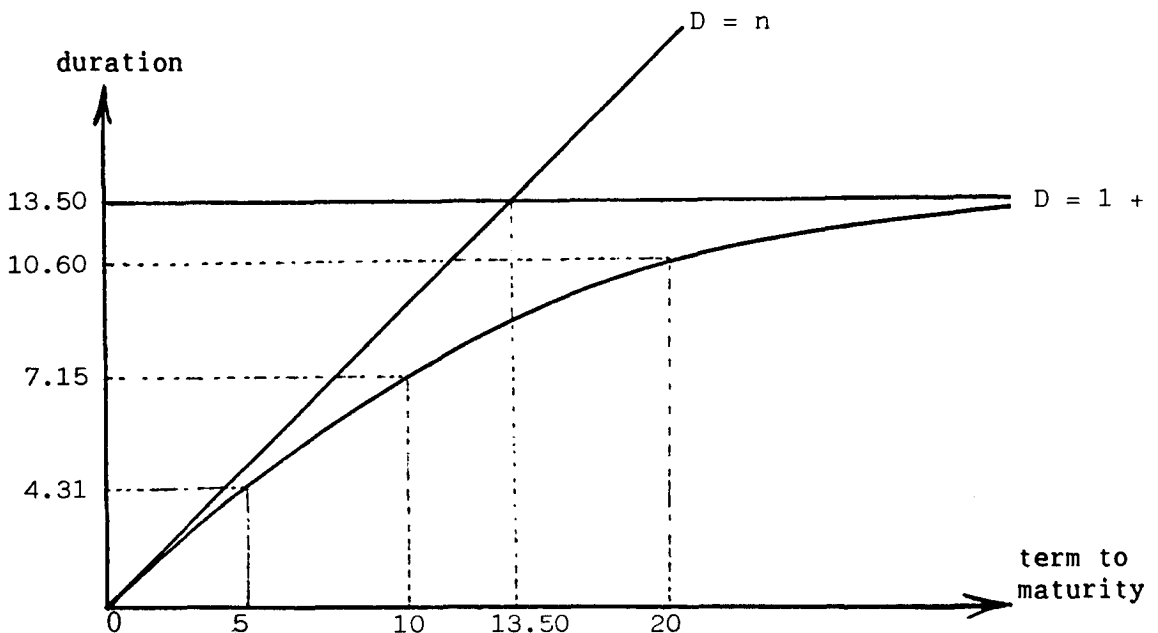
The duration of a standard bond, and hence its exposure to interest-rate risk, is a function of three parameters:

- (1) the bond's term to maturity
- (2) the bond's coupon rate, and
- (3) the bond's yield to maturity (market yield).

EXHIBIT 5

THE RELATIONSHIP BETWEEN THE DURATION AND THE TERM
TO MATURITY OF AN 8-PERCENT ANNUAL COUPON
BOND SELLING AT PAR

Maturity (n)	Corresponding duration (D)	Gap (n-D)
1 year	1.00 year	0
2 years	1.93 years	0.07 year
3 years	2.78 years	0.22 year
4 years	3.58 years	0.42 year
5 years	4.31 years	0.69 year
10 years	7.25 years	2.75 years
15 years	9.24 years	5.76 years
20 years	10.60 years	9.40 years
30 years	12.16 years	17.84 years
.	.	.
.	.	.
.	.	.
perpetual bond	13.50 years	infinity



Together these three parameters determine the bond's duration according to formula (1) in Exhibit 4. Let's examine the way each one of them affect duration.

Maturity effect

Recall our earlier observation. The duration of a coupon-bearing bond is shorter than its maturity. Only zero-coupon bonds have durations equal to their maturity. What is the relationship between maturity and duration ? Let's take an example. Consider the 8 percent annual coupon bond selling at par. Exhibit 5 illustrates the relationship between this bond's duration and its term to maturity.

Duration increases with maturity but at a comparatively smaller rate. As maturity approaches infinity, duration approaches the limit $(1 + 1/y)$ which is equal to 13.5 years when the yield is 8 percent. This is the duration of an 8-percent perpetual bond. This relationship is represented graphically in the lower part of Exhibit 5. The gap between years to maturity and duration widens as maturity grows longer⁹. The reason for this widening gap between maturity and duration is that the more distant coupon payments of longer term bonds contribute very little to these bond's present values.

Coupon effect

Recall our earlier observation. The higher a bond's coupon rate the shorter its duration. This result follows directly from our discussion in section 7. The holder of a high-coupon bond will recover part of his initial investment faster. Hence, the shorter duration or "average" maturity. Note that, in general, changes in coupon rates do not affect duration as strongly as changes in maturity

Yield effect

We have already pointed out that everything else the same, the higher a bond's yield to maturity, i.e., the higher is the level of interest rates prevailing in the market, the shorter the bond's duration. The yield effect is similar to the coupon effect. A higher yield means a faster fractional recovery of initial investment because the present value of future coupon payments is larger the higher the market yield (discount rate).

The implication of the above results is important. Let us summarize. The duration of a bond is a measure of its exposure to

interest-rate risk. Hence, A BOND'S EXPOSURE TO INTEREST-RATE RISK (WHICH CAN BE MEASURED BY ITS DURATION) IS HIGHER THE LONGER ITS MATURITY, THE LOWER ITS COUPON RATE AND THE LOWER THE GENERAL LEVEL OF INTEREST RATES.

9. The duration of a portfolio of bonds

The duration of a portfolio of bonds can be calculated according to the general formula given in Exhibit 3. Rather than calculate the duration of the cash-flow stream of one bond, we must calculate the duration of the cash-flow stream of a portfolio of bonds. Hence, the first step in calculating the duration of a bond's portfolio is to identify the portfolio's cash-flow stream.

Consider a portfolio containing two bonds. The 6-year, 8-percent-coupon bond selling at par (1000) and a 3-year, 8-percent-coupon bond also selling at par (1000). The duration of this bond portfolio is calculated in Exhibit 6 given the future cash-flow stream of the portfolio. It is equal to 3.89 years.

If the yield curve is flat, i.e., if the yield on bonds is the same for all maturities, then the duration of a portfolio of bonds is equal to the value-weighted average of the duration of the bonds that make up the portfolio. This is the case of the two bonds in our portfolio. They both have an 8-percent yield. Hence, the yield curve is flat in this case. The 6-year bond has a 5-year duration. The 3-year bond has a 2.78 year duration (see Exhibit 5). The duration of the portfolio can thus be computed as follows:

$$D = \frac{1000}{2000} (5) + \frac{1000}{2000} (2.78) = 3.89 \text{ years,}$$

which is exactly the same duration as the one found in Exhibit 6 by applying the general formula. But the calculation of the portfolio's duration as the value-weighted average of the duration of the bonds that make up that portfolio is only correct when the yield curve is flat¹⁰.

If the yield curve is not flat, taking the average duration of the bonds in a portfolio will only give an approximate value of the portfolio's duration.

EXHIBIT 6

HOW TO CALCULATE THE DURATION OF A PORTFOLIO OF BONDS

Consider the portfolio containing a 6-year, 8-percent-coupon bond selling at par (1000) and a 3-year, 8-percent-coupon bond also selling at par (1000). Apply the general duration formula given in Exhibit 3 to the portfolio's cash-flow stream. You find a duration of 3.89 years.

	CF_t t (3-year bond)	CF_t (6-year bond)	CF_t^* (portfolio)	DF_t	$CF_t^* \cdot DF_t$	$CF_t^* \cdot DF_t \cdot t$
1	80	80	160	.9259	148.14	148.14
2	80	80	160	.8573	137.18	274.36
3	1080	80	1160	.7938	920.85	2762.55
4	0	80	80	.7350	58.80	235.20
5	0	80	80	.6806	54.45	272.25
6	0	1080	1080	.6302	680.58	4083.48
					<u>2000.00</u>	<u>7775.98</u>

$$D (\text{portfolio}) = \frac{7775.98}{2000} = 3.89 \text{ years}$$

Note that since a portfolio of bonds has a measurable duration, two portfolios with the same duration must have the same exposure to interest-rate risk even if their composition differs significantly. Another way of looking at this result is that a portfolio's exposure to interest-rate risk can be managed by modifying its duration via portfolio rebalancing. This is examined in the next section in the context of immunization strategies.

10. How to implement an immunization strategy

The duration given by formula (1) in Exhibit 4 is known as Macaulay's¹¹ duration. It is the simplest of many duration formulas. But it is based on a restrictive assumption. It assumes that the yield curve is flat, i.e., that the yield on bonds is independent of their maturity. In general, however, the yield curve is rising. Sometimes, it is declining. When we use Macaulay's duration for bond immunization, the assumption is that the flat yield curve changes in a parallel fashion immediately after the bond is purchased. This is what we called "conventional" immunization in section 4. In this section we conclude with an illustration of how one can implement a conventional immunization strategy. In Appendix Two we review some of the alternative measures of duration which do not assume a flat yield curve that changes in a parallel fashion.

But using Macaulay's duration to implement immunization raises an important question. How do conventional immunization strategies, based on Macaulay's duration, compare with strategies that use more complex measures of duration? Most empirical studies indicate that immunization strategies based on Macaulay's duration perform at least as well as more sophisticated rivals¹². They also outperform maturity-based strategies¹³. Hence, in practice most immunization strategies are based on Macaulay's duration. In what follows we explain how this is done.

To show how conventional immunization strategy is implemented go back to the numerical illustration of portfolio duration given in the previous section. Suppose that a portfolio manager has a planning horizon of 3.89 years over which he wants a guaranteed return of at least 8 percent. Assume that only two kinds of bonds are available for investment: 6-year, 8-percent coupon bonds and 3-year, 8-percent coupon bonds. An immunization strategy requires the construction of a bond

portfolio with an average yield of 8 percent and a duration equal to the manager's planning horizon, i.e., a duration equal to 3.89 years. This is exactly the portfolio described in the previous section which contains an equal amount of 6-year and 3-year bonds¹⁴.

In order to achieve continual immunization, the portfolio duration must be kept equal to the remainder of the 3.89-year planning horizon. But the passage of time will create a mismatch between the duration of the portfolio and the remainder of the planning horizon. To see this, suppose that one year has passed and that the market yield is 8 percent¹⁵. The remainder of the planning horizon is 2.89 years (the original 3.89 years less one year) and the bonds in the portfolio are now 5-year and 2-year bonds with durations of 4.31 years and 1.93 years, respectively (see Exhibit 5). As a result, the duration of the bond portfolio one year after its original construction is equal to:

$$D = \frac{1000}{2000} (4.31) + \frac{1000}{2000} (1.91) = 3.11 \text{ years.}$$

The planning horizon went from 3.89 years to 2.89 years but the portfolio duration went from 3.89 years to 3.11 years. This, of course, is a manifestation of the phenomenon illustrated in Exhibit 5: as the targeted date approaches, the durations of the component bonds get shorter but at a slower rate than the passage of time. As a consequence, one year after its initial construction the portfolio is no longer immunized. To re-immunize it, it must be rebalanced so as to bring its duration from 3.11 years down to 2.89 years (the remainder of the planning horizon). This can be done by reinvesting the portfolio's first-year cash inflow (160 of coupon payments) in the bond with the shortest duration (the 2-year bond). This will shorten the portfolio duration to¹⁶:

$$D = \frac{1000}{2160} (4.31) + \frac{1160}{2160} (1.91) = 3.02 \text{ years.}$$

The reinvestment of coupon payments is not sufficient to bring the portfolio's duration down to 2.89 years. In this case some 5-year bonds must be sold and the proceed used to purchase 2-year bonds¹⁷. The following year, a similar rebalancing must be carried out so that the resulting portfolio has a duration of 1.89 years, and so on until the targeted date is reached. The strategy is to keep the duration of the portfolio always equal to the length of time until the original targeted

horizon is attained¹⁸. By following this duration-matching strategy the portfolio will be immunized against small changes in interest rates. However, if the yield curve is not flat and if interest-rate fluctuations are large, interest-rate risk will not be eliminated but it should be greatly reduced.

APPENDIX ONE

BOND CONVEXITY AND ITS RELATIONSHIP
TO BOND DURATION

We have seen in section 2 and Exhibit 1 that the duration formula provides good estimates of a bond's percentage price change only for very small changes in yield (a few basis points). For large changes in yield the duration formula is no longer accurate. This is due to the fact that the relationship between a bond's price and its yield is convex: as the yield increases the price of the bonds drops at a decreasing rate. The higher the yield, the less sensitive is the bond's price to a change in yield.

If we take into account the convexity of the price-yield relationship we can obtain a more accurate formula to calculate a bond's percentage price change in response to relatively large changes in yield. We first define convexity and then present a formula that links duration and convexity to percentage price change.

A bond's convexity (CX) or curvature can be measured as follows:

$$CX = 10^8 \left[\frac{P(y+.0001) - P(y)}{P(y)} + \frac{P(y-.0001) - P(y)}{P(y)} \right],$$

where $P(y+.0001)$ is the bond's price at the yield y plus one basis point (one hundredth of one percent) and $P(y-.0001)$ is the bond's price at the yield y minus one basis point. Consider the 6-year, 8-percent coupon bond selling at par. In this case $y=.08$ and $P(y)=1000$. From Exhibit 1 we get $P(y+.0001) \equiv P(.0801) = 999.53785$ and $P(y - .0001) \equiv P(.0799) = 1000.46243$. Plugging these numbers in the formula for convexity we find that convexity is equal to 28:

$$CX = 10^8 \left[\frac{999.53785 - 1000}{1000} + \frac{1000.46243 - 1000}{1000} \right] = 28 .$$

Now, it can be shown that:

$$\frac{\Delta P}{P} = -(MD) \cdot (\Delta y) + \frac{1}{2} (CX) \cdot (\Delta y)^2 .$$

The first term in the above equation is the portion of the bond's percentage price change that is explained by the bond's duration. It is the duration formula given in section 2. The second term in the equation is the portion of the bond's percentage price change that is explained by the bond's convexity. Together, duration and convexity provide a more accurate value of a bond's percentage price change given a change in yield. But if the change in yield is relatively small the second term can be ignored and we are left with the duration formula. To illustrate how the formula works, refer to Exhibit 1 in the text. Suppose that the yield moves from 8 percent to 10 percent, the exact percentage price change is about 8.71 percent. The percentage price change given by the duration formula is about 9.24 percent, an overestimation of about 53 basis. Using the formula above we get:

$$\frac{\Delta P}{P} = -(4.623)(.02) + \frac{1}{2} (28)(.02)^2 = 8.69 \text{ percent,}$$

which is only two basis points away from the exact value of 8.71 percent¹⁹. Note that convexity has some relevance to bond portfolio management. Everything else the same, more convexity is preferred to less convexity since more convexity means that the increase in the bond's price will be larger when the market yield drops and the decrease in the bond's price will be smaller when the market yield rises. Hence, if two portfolios have the same duration, the one with the higher convexity should be preferred.

APPENDIX TWO

ALTERNATIVE MEASURES OF DURATION

The measure of duration discussed in the article is referred to as Macaulay's duration. It is given in Exhibit 3:

$$D_1 = \frac{1}{P_0} \sum_{t=1}^n (CF_t)(1+y)^{-t} \quad ,$$

where P_0 is the present value of the cash flow stream CF_t . Macaulay's duration D_1 makes two assumptions. First, the yield curve is flat and hence there exists a unique discount rate y that is used to discount each one of the n cash flows that make up the cash flow stream. Second, when the level of interest rates changes, all rates change by the same magnitude and hence the flat yield curve shifts in a parallel fashion. That is:

$$(\Delta y)_1 = \dots = (\Delta y)_t = \dots = (\Delta y)_n \quad .$$

If we now assume that the yield is not flat, we can no longer use a unique discount rate to calculate duration. When the yield curve is not flat, to each period t corresponds a different discount rate y_t called the t -period discount rate. Below we give two alternative measures of duration that do not assume flat yield curves. Note that the immunization strategy we described in section 10 still applies to the alternative duration measures given below. One must simply modify duration according to its alternative measure and proceed as in the case of conventional immunization²⁰.

Case 1: The yield curve is not flat and the percentage change in any t -period spot rate is equal to the percentage change in the first period spot rate. That is:

$$\frac{\Delta y_t}{(1+y_t)} = \frac{\Delta y_1}{(1+y_1)} \quad .$$

In this case it can be shown that²¹:

$$D_2 = \frac{1}{P_0} \sum_{t=1}^n (CF_t)(1+y_t)^{-t}(t) .$$

Note the difference between D_1 and D_2 . In D_2 , the t -period cash flow is discounted at the t -period spot rate rather than having all cash flows discounted at a unique discount rate.

Case 2: The yield curve is not flat and the longer is the rate the smaller is the percentage change in the rate. That is:

$$\frac{\Delta y_t}{(1+y_t)} = \alpha^t \left[\frac{\Delta y_1}{(1+y_1)} \right] ,$$

with α smaller than one. The assumption is consistent with the fact that long-term rates change less than short-term rates.

In this case it can be shown that²²:

$$D_3 = \frac{1}{P_0} \sum_{t=1}^n (CF_t)(1+y_t)^{-t}(\alpha^t)(t) .$$

This measure of duration requires the specification of the coefficient α .

Footnotes

1. Price = (coupon)(annuity discount factor) + (face)(discount factor)
Price (8½% and 6 years) = (80)(4.554) + (100)(.6129) = 97.72.
2. Note that the percentage change in the price of the bond is not symmetrical. A ½ percentage increase in the yield is associated with a 2.28 percent drop in price but a ½ percentage decrease in yield is associated with a 2.35 percent rise in price. This phenomenon is due to the fact that the relationship between a bond's price and its yield is convex rather than linear. See section 2 and Appendix One for details.
3. This statement assumes a flat yield curve (i.e., the market yield of all bonds is the same regardless of their term to maturity) and parallel shifts in the yield curve (i.e., the change in yield is the same for all bonds regardless of their term to maturity). See section 3 and Appendix Two.
4. See, for example, Hawawini (1982) for proof.
5. See McEnally (1980) for a similar example.
6. Note that duration is calculated by discounting the first and the second cash flows at the same rate of 10 percent. This is what is meant by a "flat yield curve assumption". If the yield were rising or declining we would have discounted the two cash flows at different rates as specified by the shape of the yield curve. See Appendix Two.
7. Proofs of these formulas are given in Hawawini (1984) and (1987). The original duration formula was established by Macaulay (1936). Most of the early papers describing the development of duration are reproduced in Hawawini (1982) including Macaulay's contribution. Recent developments are found in Hawawini (1982) and Bierwag et al. (1983 a,b).
8. The concept of duration as a measure of interest-rate risk exposure can be extended to financial instruments other than "straight" bonds. It has been applied to equity, options as well as bonds with options features such as callable bonds. See the articles in Platt (1986).
9. The curve at the lower part of Exhibit 5 illustrates the case of a bond selling at par. A similar curve applies to bond's selling at a premium but not for bonds selling at a deep discount. For these bonds, the curve may intersect the $D = \frac{1}{(1+i)}$ line and then converge towards that line. In other words, for some bonds selling at a deep discount, duration and maturity may be inversely related over some maturity range. See Hawawini (1982, 1984).
10. When the yield curve is flat, the yield to maturity of all bonds in the portfolio is the same and hence the portfolio's yield is equal to that of the bonds in the portfolio, and the portfolio's duration is a weighted average of the bond's duration.
11. See Macaulay (1936), Chapter III

12. See the articles in Bierwag et al. (1983 a) and the article by Schaeffer (1984).
13. See Bierwag et al. (1987)
14. The number of bonds one must buy today in order to achieve immunization depends on the dollar amount one wishes to have at the end of the 3.89-year horizon. Suppose that the portfolio manager has a liability of \$1,000,000 due in 3.89 years. How many bonds should he buy today to achieve immunization? The present value of the liability at 8 percent is \$741,068. Hence \$370,534 worth of 6-year bonds and \$370,534 worth of 3-year bonds must be purchased (equal to allocation in order to get a 3.89-year duration for the portfolio). Since the bonds sell for \$1,000 a unit, we need about 371 bonds of each maturity.
15. For the sake of exposition and to facilitate the calculations we assume that the market yield is still at 8 percent. But the conclusions are the same if the yield changes.
16. We assume that we can buy and sell a fraction of a bond.
17. How much of the 5-year bond must be sold to bring duration down to 2.89 years? It is the amount x that solves the equation:

$$D = \frac{1000 - x}{2160} (4.31) + \frac{1160 + x}{2160} (1.91) = 2.89 .$$

It is equal to 118, i.e. \$118 worth of 5-year bonds must be sold and an equal amount of 2-year bonds purchased.

18. Note that the frequency of portfolio rebalancing can be increased. For example, rebalancing every 6 months instead of every year. But frequent portfolio rebalancing will raise transaction costs. There is a trade-off between the cost of frequent rebalancing and the benefit of frequent duration matching.
19. For additional information see Klotz (1985).
20. The immunization strategies discussed in this article are known as one-factor immunization models. There are also so-called two-factor models. In the former case, the change in yield is determined by a single factor (e.g., long-term rate). In the latter, it is determined by two factors (e.g., the short-term and the long-term rates). Two-factor models do not seem to outperform one-factor models. See Schaeffer (1984).
21. See Elton and Gruber (1984), Chapter 19.
22. See Elton and Gruber (1984), Chapter 19.

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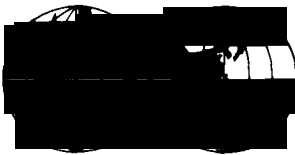
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