

Chapter 1

Portfolio Theory with Matrix Algebra

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When working with large portfolios, the algebra of representing portfolio expected returns and variances becomes cumbersome. The use of matrix (linear) algebra can greatly simplify many of the computations. Matrix algebra formulations are also very useful when it comes time to do actual computations on the computer. The matrix algebra formulas are easy to translate into matrix programming languages like R. Popular spreadsheet programs like Microsoft Excel, which are the workhorse programs of many financial houses, can also handle basic matrix calculations. All of this makes it worthwhile to become familiar with matrix techniques for portfolio calculations.

1.1 Portfolios with Three Risky Assets

Consider a three asset portfolio problem with assets denoted A , B and C . Let R_i ($i = A, B, C$) denote the return on asset i and assume that the constant expected return (CER) model holds:

$$R_i \sim iid N(\mu_i, \sigma_i^2)$$
$$\text{cov}(R_i, R_j) = \sigma_{ij}.$$

Example 1 *Three asset example data*

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Stock i	μ_i	σ_i	Pair (i,j)	σ_{ij}
A	0.0427	0.1000	(A,B)	0.0018
B	0.0015	0.1044	(A,C)	0.0011
C	0.0285	0.1411	(B,C)	0.0026

Table 1.1: Three asset example data.

Table 1.1 gives example data on monthly means, variances and covariances for the continuously compounded returns on Microsoft, Nordstrom and Starbucks (assets A, B and C) based on sample statistics computed over the five-year period January, 1995 through January, 2000¹. The values of μ_i and σ_i (risk-return trade-offs) are shown in Figure 1.1. Clearly, Microsoft provides the best risk-return trade-off and Nordstrom provides with worst.

■

Let x_i denote the share of wealth invested in asset i ($i = A, B, C$), and assume that all wealth is invested in the three assets so that $x_A + x_B + x_C = 1$. The portfolio return, $R_{p,x}$, is the random variable

$$R_{p,x} = x_A R_A + x_B R_B + x_C R_C. \quad (1.1)$$

The subscript “ x ” indicates that the portfolio is constructed using the x -weights x_A , x_B and x_C . The expected return on the portfolio is

$$\mu_{p,x} = E[R_{p,x}] = x_A \mu_A + x_B \mu_B + x_C \mu_C, \quad (1.2)$$

and the variance of the portfolio return is

$$\begin{aligned} \sigma_{p,x}^2 &= \text{var}(R_{p,x}) \\ &= x_A^2 \sigma_A^2 + x_B^2 \sigma_B^2 + x_C^2 \sigma_C^2 + 2x_A x_B \sigma_{AB} + 2x_A x_C \sigma_{AC} + 2x_B x_C \sigma_{BC}. \end{aligned} \quad (1.3)$$

Notice that variance of the portfolio return depends on three variance terms and six covariance terms. Hence, with three assets there are twice as many covariance terms than variance terms contributing to portfolio variance. Even with three assets, the algebra representing the portfolio characteristics (1.1) - (1.3) is cumbersome. We can greatly simplify the portfolio algebra using matrix notation.

¹This example data is also analyzed in the Excel spreadsheet 3firmExample.xls.

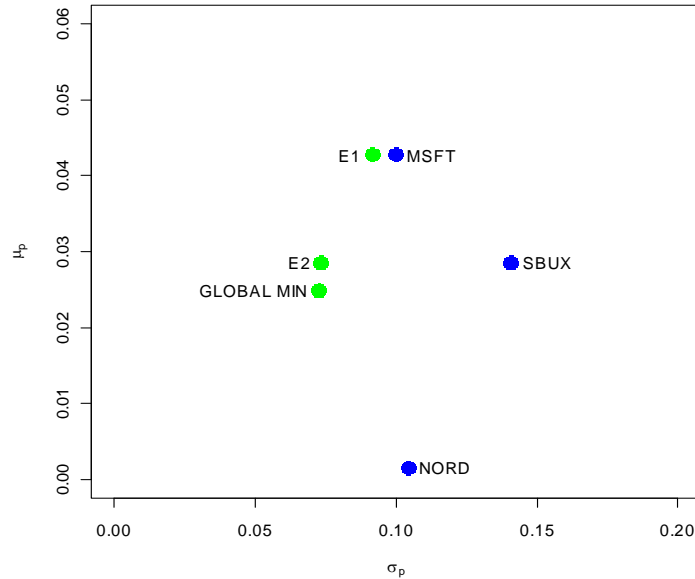


Figure 1.1: Risk-return tradeoffs among three asset portfolios. The portfolio labeled “E1” is the efficient portfolio with the same expected return as Microsoft; the portfolio labeled “E2” is the efficient portfolio with the same expected return as Starbux. The portfolio labeled GLOBAL MIN is the minimum variance portfolio consisting of Microsoft, Nordstrom and Starbucks, respectively.

1.1.1 Portfolio Characteristics Using Matrix Notation

Define the following 3×1 column vectors containing the asset returns and portfolio weights

$$\mathbf{R} = \begin{pmatrix} R_A \\ R_B \\ R_C \end{pmatrix}, \quad \mathbf{x} = \begin{pmatrix} x_A \\ x_B \\ x_C \end{pmatrix}.$$

In matrix notation we can lump multiple returns in a single vector which we denote by \mathbf{R} . Since each of the elements in \mathbf{R} is a random variable we call \mathbf{R} a *random vector*. The probability distribution of the random vector \mathbf{R} is

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simply the joint distribution of the elements of \mathbf{R} . In the CER model all returns are jointly normally distributed and this joint distribution is completely characterized by the means, variances and covariances of the returns. We can easily express these values using matrix notation as follows. The 3×1 vector of portfolio expected values is

$$E[\mathbf{R}] = E \left[\begin{pmatrix} R_A \\ R_B \\ R_C \end{pmatrix} \right] = \begin{pmatrix} E[R_A] \\ E[R_B] \\ E[R_C] \end{pmatrix} = \begin{pmatrix} \mu_A \\ \mu_B \\ \mu_C \end{pmatrix} = \boldsymbol{\mu},$$

and the 3×3 covariance matrix of returns is

$$\begin{aligned} \text{var}(\mathbf{R}) &= \begin{pmatrix} \text{var}(R_A) & \text{cov}(R_A, R_B) & \text{cov}(R_A, R_C) \\ \text{cov}(R_B, R_A) & \text{var}(R_B) & \text{cov}(R_B, R_C) \\ \text{cov}(R_C, R_A) & \text{cov}(R_C, R_B) & \text{var}(R_C) \end{pmatrix} \\ &= \begin{pmatrix} \sigma_A^2 & \sigma_{AB} & \sigma_{AC} \\ \sigma_{AB} & \sigma_B^2 & \sigma_{BC} \\ \sigma_{AC} & \sigma_{BC} & \sigma_C^2 \end{pmatrix} = \boldsymbol{\Sigma}. \end{aligned}$$

Notice that the covariance matrix is symmetric (elements off the diagonal are equal so that $\boldsymbol{\Sigma} = \boldsymbol{\Sigma}'$, where $\boldsymbol{\Sigma}'$ denotes the transpose of $\boldsymbol{\Sigma}$) since $\text{cov}(R_A, R_B) = \text{cov}(R_B, R_A)$, $\text{cov}(R_A, R_C) = \text{cov}(R_C, R_A)$ and $\text{cov}(R_B, R_C) = \text{cov}(R_C, R_B)$.

Example 2 *Example return data using matrix notation*

Using the example data in Table 1.1 we have

$$\begin{aligned} \boldsymbol{\mu} &= \begin{pmatrix} \mu_A \\ \mu_B \\ \mu_C \end{pmatrix} = \begin{pmatrix} 0.0427 \\ 0.0015 \\ 0.0285 \end{pmatrix}, \\ \boldsymbol{\Sigma} &= \begin{pmatrix} 0.0100 & 0.0018 & 0.0011 \\ 0.0018 & 0.0109 & 0.0026 \\ 0.0011 & 0.0026 & 0.0199 \end{pmatrix}. \end{aligned}$$

In R, these values are created using

```
> asset.names <- c("MSFT", "NORD", "SBUX")
> mu.vec = c(0.0427, 0.0015, 0.0285)
> names(mu.vec) = asset.names
> sigma.mat = matrix(c(0.0100, 0.0018, 0.0011,
+                       0.0018, 0.0109, 0.0026,
+                       0.0011, 0.0026, 0.0199),
+                     nrow=3, ncol=3)
> dimnames(sigma.mat) = list(asset.names, asset.names)
> mu.vec
  MSFT  NORD  SBUX
0.0427 0.0015 0.0285
> sigma.mat
      MSFT  NORD  SBUX
MSFT 0.0100 0.0018 0.0011
NORD 0.0018 0.0109 0.0026
SBUX 0.0011 0.0026 0.0199
```

■

The return on the portfolio using matrix notation is

$$R_{p,x} = \mathbf{x}'\mathbf{R} = (x_A, x_B, x_C) \cdot \begin{pmatrix} R_A \\ R_B \\ R_C \end{pmatrix} = x_A R_A + x_B R_B + x_C R_C.$$

Similarly, the expected return on the portfolio is

$$\mu_{p,x} = E[\mathbf{x}'\mathbf{R}] = \mathbf{x}'E[\mathbf{R}] = \mathbf{x}'\boldsymbol{\mu} = (x_A, x_B, x_C) \cdot \begin{pmatrix} \mu_A \\ \mu_B \\ \mu_C \end{pmatrix} = x_A \mu_A + x_B \mu_B + x_C \mu_C.$$

The variance of the portfolio is

$$\begin{aligned} \sigma_{p,x}^2 &= \text{var}(\mathbf{x}'\mathbf{R}) = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x} = (x_A, x_B, x_C) \cdot \begin{pmatrix} \sigma_A^2 & \sigma_{AB} & \sigma_{AC} \\ \sigma_{AB} & \sigma_B^2 & \sigma_{BC} \\ \sigma_{AC} & \sigma_{BC} & \sigma_C^2 \end{pmatrix} \begin{pmatrix} x_A \\ x_B \\ x_C \end{pmatrix} \\ &= x_A^2 \sigma_A^2 + x_B^2 \sigma_B^2 + x_C^2 \sigma_C^2 + 2x_A x_B \sigma_{AB} + 2x_A x_C \sigma_{AC} + 2x_B x_C \sigma_{BC}. \end{aligned}$$

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The condition that the portfolio weights sum to one can be expressed as

$$\mathbf{x}'\mathbf{1} = (x_A, x_B, x_C) \cdot \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = x_A + x_B + x_C = 1,$$

where $\mathbf{1}$ is a 3×1 vector with each element equal to 1.

Consider another portfolio with weights $\mathbf{y} = (y_A, y_B, y_C)'$. The return on this portfolio is

$$R_{p,y} = \mathbf{y}'\mathbf{R} = y_A R_A + y_B R_B + y_C R_C.$$

Later on we will need to compute the covariance between the return on portfolio \mathbf{x} and the return on portfolio \mathbf{y} , $\text{cov}(R_{p,x}, R_{p,y})$. Using matrix algebra, this covariance can be computed as

$$\begin{aligned} \sigma_{xy} &= \text{cov}(R_{p,x}, R_{p,y}) = \text{cov}(\mathbf{x}'\mathbf{R}, \mathbf{y}'\mathbf{R}) \\ &= \mathbf{x}'\Sigma\mathbf{y} = (x_A, x_B, x_C) \cdot \begin{pmatrix} \sigma_A^2 & \sigma_{AB} & \sigma_{AC} \\ \sigma_{AB} & \sigma_B^2 & \sigma_{BC} \\ \sigma_{AC} & \sigma_{BC} & \sigma_C^2 \end{pmatrix} \begin{pmatrix} y_A \\ y_B \\ y_C \end{pmatrix} \\ &= x_A y_A \sigma_A^2 + x_B y_B \sigma_B^2 + x_C y_C \sigma_C^2 \\ &\quad + (x_A y_B + x_B y_A) \sigma_{AB} + (x_A y_C + x_C y_A) \sigma_{AC} + (x_B y_C + x_C y_B) \sigma_{BC}. \end{aligned}$$

Example 3 *Portfolio computations in R*

Consider an equally weighted portfolio with $x_A = x_B = x_C = 1/3$. This portfolio has return $R_{p,x} = \mathbf{x}'\mathbf{R}$ where $\mathbf{x} = (1/3, 1/3, 1/3)'$. Using R, the portfolio mean and variance are

```
> x.vec = rep(1,3)/3
> names(x.vec) = asset.names
> mu.p.x = crossprod(x.vec, mu.vec)
> sig2.p.x = t(x.vec)%*%sigma.mat%*%x.vec
> sig.p.x = sqrt(sig2.p.x)
> mu.p.x
[ ,1]
```

```
[1,] 0.02423
> sig.p.x
      [,1]
[1,] 0.07587
```

Next, consider another portfolio with weight vector $\mathbf{y} = (y_A, y_B, y_C)' = (0.8, 0.4, -0.2)'$ and return $R_{p,y} = \mathbf{y}'\mathbf{R}$. The covariance between $R_{p,x}$ and $R_{p,y}$ is

```
> y.vec = c(0.8, 0.4, -0.2)
> names(x.vec) = asset.names
> sig.xy = t(x.vec)%*%sigma.mat%*%y.vec
> sig.xy
      [,1]
[1,] 0.003907
```

■

1.1.2 Finding the Global Minimum Variance Portfolio

The global minimum variance portfolio $\mathbf{m} = (m_A, m_B, m_C)'$ for the three asset case solves the constrained minimization problem

$$\begin{aligned} \min_{m_A, m_B, m_C} \sigma_{p,m}^2 &= m_A^2 \sigma_A^2 + m_B^2 \sigma_B^2 + m_C^2 \sigma_C^2 \\ &+ 2m_A m_B \sigma_{AB} + 2m_A m_C \sigma_{AC} + 2m_B m_C \sigma_{BC} \\ \text{s.t. } m_A + m_B + m_C &= 1. \end{aligned} \quad (1.4)$$

The Lagrangian for this problem is

$$\begin{aligned} L(m_A, m_B, m_C, \lambda) &= m_A^2 \sigma_A^2 + m_B^2 \sigma_B^2 + m_C^2 \sigma_C^2 \\ &+ 2m_A m_B \sigma_{AB} + 2m_A m_C \sigma_{AC} + 2m_B m_C \sigma_{BC} \\ &+ \lambda(m_A + m_B + m_C - 1), \end{aligned}$$

and the first order conditions (FOCs) for a minimum are

$$\begin{aligned} 0 &= \frac{\partial L}{\partial m_A} = 2m_A \sigma_A^2 + 2m_B \sigma_{AB} + 2m_C \sigma_{AC} + \lambda, \\ 0 &= \frac{\partial L}{\partial m_B} = 2m_B \sigma_B^2 + 2m_A \sigma_{AB} + 2m_C \sigma_{BC} + \lambda, \\ 0 &= \frac{\partial L}{\partial m_C} = 2m_C \sigma_C^2 + 2m_A \sigma_{AC} + 2m_B \sigma_{BC} + \lambda, \\ 0 &= \frac{\partial L}{\partial \lambda} = m_A + m_B + m_C - 1. \end{aligned} \quad (1.5)$$

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The FOCs (1.5) gives four linear equations in four unknowns which can be solved to find the global minimum variance portfolio weights m_A, m_B and m_C .

Using matrix notation, the problem (1.4) can be concisely expressed as

$$\min_{\mathbf{m}} \sigma_{p,m}^2 = \mathbf{m}'\Sigma\mathbf{m} \text{ s.t. } \mathbf{m}'\mathbf{1} = 1. \quad (1.6)$$

The four linear equation describing the first order conditions (1.5) has the matrix representation

$$\begin{pmatrix} 2\sigma_A^2 & 2\sigma_{AB} & 2\sigma_{AC} & 1 \\ 2\sigma_{AB} & 2\sigma_B^2 & 2\sigma_{BC} & 1 \\ 2\sigma_{AC} & 2\sigma_{BC} & 2\sigma_C^2 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} m_A \\ m_B \\ m_C \\ \lambda \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix},$$

or, more concisely,

$$\begin{pmatrix} 2\Sigma & \mathbf{1} \\ \mathbf{1}' & 0 \end{pmatrix} \begin{pmatrix} \mathbf{m} \\ \lambda \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ 1 \end{pmatrix}. \quad (1.7)$$

The system (1.7) is of the form

$$\mathbf{A}_m \mathbf{z}_m = \mathbf{b},$$

where

$$\mathbf{A}_m = \begin{pmatrix} 2\Sigma & \mathbf{1} \\ \mathbf{1}' & 0 \end{pmatrix}, \quad \mathbf{z}_m = \begin{pmatrix} \mathbf{m} \\ \lambda \end{pmatrix} \text{ and } \mathbf{b} = \begin{pmatrix} \mathbf{0} \\ 1 \end{pmatrix}.$$

The solution for \mathbf{z}_m is then

$$\mathbf{z}_m = \mathbf{A}_m^{-1} \mathbf{b}. \quad (1.8)$$

The first three elements of \mathbf{z}_m are the portfolio weights $\mathbf{m} = (m_A, m_B, m_C)'$ for the global minimum variance portfolio with expected return $\mu_{p,m} = \mathbf{m}'\boldsymbol{\mu}$ and variance $\sigma_{p,m}^2 = \mathbf{m}'\Sigma\mathbf{m}$.

Example 4 *Global minimum variance portfolio for example data*

Using the data in Table 1, we can use R to compute the global minimum variance portfolio weights from (1.8) as follows:


```

> top.mat = cbind(2*sigma.mat, rep(1, 3))
> bot.vec = c(rep(1, 3), 0)
> Am.mat = rbind(top.mat, bot.vec)
> b.vec = c(rep(0, 3), 1)
> z.m.mat = solve(Am.mat)%*%b.vec
> m.vec = z.m.mat[1:3,1]
> m.vec
  MSFT  NORD  SBUX
0.4411 0.3656 0.1933

```

Hence, the global minimum variance portfolio has portfolio weights $m_{msft} = 0.4411$, $m_{nord} = 0.3656$ and $m_{sbux} = 0.1933$, and is given by the vector

$$\mathbf{m} = (0.4411, 0.3656, 0.1933)'. \quad (1.9)$$

The expected return on this portfolio, $\mu_{p,m} = \mathbf{m}'\boldsymbol{\mu}$, is

```

> mu.gmin = as.numeric(crossprod(m.vec, mu.vec))
> mu.gmin
[1] 0.02489

```

The portfolio variance, $\sigma_{p,m}^2 = \mathbf{m}'\boldsymbol{\Sigma}\mathbf{m}$, and standard deviation, $\sigma_{p,m}$, are

```

> sig2.gmin = as.numeric(t(m.vec)%*%sigma.mat)%*%m.vec)
> sig.gmin = sqrt(sig2.gmin)
> sig2.gmin
[1] 0.005282
> sig.gmin
[1] 0.07268

```

In Figure 1.1, this portfolio is labeled “global min”.■

Alternative derivation of global minimum variance portfolio

The first order conditions (1.5) from the optimization problem (1.6) can be expressed in matrix notation as

$$\mathbf{0}_{(3 \times 1)} = \frac{\partial L(\mathbf{m}, \lambda)}{\partial \mathbf{m}} = 2 \cdot \boldsymbol{\Sigma}\mathbf{m} + \lambda \cdot \mathbf{1}, \quad (1.10)$$

$$0_{(1 \times 1)} = \frac{\partial L(\mathbf{m}, \lambda)}{\partial \lambda} = \mathbf{m}'\mathbf{1} - 1. \quad (1.11)$$

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Using (1.10), first solve for \mathbf{m} :

$$\mathbf{m} = -\frac{1}{2} \cdot \lambda \Sigma^{-1} \mathbf{1}.$$

Next, multiply both sides by $\mathbf{1}'$ and use (1.11) to solve for λ :

$$\begin{aligned} 1 &= \mathbf{1}'\mathbf{m} = -\frac{1}{2} \cdot \lambda \mathbf{1}'\Sigma^{-1}\mathbf{1} \\ \Rightarrow \lambda &= -2 \cdot \frac{1}{\mathbf{1}'\Sigma^{-1}\mathbf{1}}. \end{aligned}$$

Finally, substitute the value for λ back into (1.10) to solve for \mathbf{m} :

$$\mathbf{m} = -\frac{1}{2} (-2) \frac{1}{\mathbf{1}'\Sigma^{-1}\mathbf{1}} \Sigma^{-1}\mathbf{1} = \frac{\Sigma^{-1}\mathbf{1}}{\mathbf{1}'\Sigma^{-1}\mathbf{1}}. \quad (1.12)$$

Example 5 *Finding global minimum variance portfolio for example data*

Using the data in Table 1, we can use R to compute the global minimum variance portfolio weights from (1.12) as follows:

```
> one.vec = rep(1, 3)
> sigma.inv.mat = solve(sigma.mat)
> top.mat = sigma.inv.mat%%one.vec
> bot.val = as.numeric((t(one.vec)%*%sigma.inv.mat)%*%one.vec)
> m.mat = top.mat/bot.val
> m.mat[,1]
  MSFT  NORD  SBUX
0.4411 0.3656 0.1933
```

■

1.1.3 Finding Efficient Portfolios

The investment opportunity set is the set of portfolio expected return, μ_p , and portfolio standard deviation, σ_p , values for all possible portfolios whose weights sum to one. As in the two risky asset case, this set can be described in a graph with μ_p on the vertical axis and σ_p on the horizontal axis. With two assets, the investment opportunity set in (μ_p, σ_p) -space lies on a curve (one side of a hyperbola). With three or more assets, the investment opportunity set in (μ_p, σ_p) -space is described by set of values whose general shape

is complicated and depends crucially on the covariance terms σ_{ij} . However, we do not have to fully characterize the entire investment opportunity set. If we assume that investors choose portfolios to maximize expected return subject to a target level of risk, or, equivalently, to minimize risk subject to a target expected return, then we can simplify the asset allocation problem by only concentrating on the set of efficient portfolios. These portfolios lie on the boundary of the investment opportunity set above the global minimum variance portfolio. This is the framework originally developed by Harry Markowitz, the father of portfolio theory and winner of the Nobel Prize in economics.

Following Markowitz, we assume that investors wish to find portfolios that have the best expected return-risk trade-off. Markowitz characterized these efficient portfolios in two equivalent ways. In the first way, investors seek to find portfolios that maximize portfolio expected return for a given level of risk as measured by portfolio variance. Let $\sigma_{p,0}^2$ denote a target level of risk. Then Harry Markowitz characterized the constrained maximization problem to find an efficient portfolio as

$$\begin{aligned} \max_{\mathbf{x}} \mu_p &= \mathbf{x}'\boldsymbol{\mu} \text{ s.t.} \\ \sigma_p^2 &= \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x} = \sigma_{p,0}^2 \text{ and } \mathbf{x}'\mathbf{1} = 1. \end{aligned} \quad (1.13)$$

Markowitz showed that the investor's problem of maximizing portfolio expected return subject to a target level of risk has an equivalent dual representation in which the investor minimizes the risk of the portfolio (as measured by portfolio variance) subject to a target expected return level. Let $\mu_{p,0}$ denote a target expected return level. Then the dual problem is the constrained minimization problem

$$\begin{aligned} \min_{\mathbf{x}} \sigma_{p,x}^2 &= \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x} \text{ s.t.} \\ \mu_p &= \mathbf{x}'\boldsymbol{\mu} = \mu_{p,0}, \text{ and } \mathbf{x}'\mathbf{1} = 1, \end{aligned} \quad (1.14)$$

To find efficient portfolios of risky assets in practice, the dual problem (1.14) is most often solved. This is partially due to computational conveniences and partly due to investors being more willing to specify target expected returns rather than target risk levels. The efficient portfolio frontier is a graph of μ_p versus σ_p values for the set of efficient portfolios generated by solving (1.14) for all possible target expected return levels $\mu_{p,0}$ above the expected return on the global minimum variance portfolio. Just as in the two asset case, the

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resulting efficient frontier will resemble one side of an hyperbola and is often called the “Markowitz bullet”.

To solve the constrained minimization problem (1.14), first form the Lagrangian function

$$L(x, \lambda_1, \lambda_2) = \mathbf{x}'\Sigma\mathbf{x} + \lambda_1(\mathbf{x}'\boldsymbol{\mu} - \mu_{p,0}) + \lambda_2(\mathbf{x}'\mathbf{1} - 1).$$

Because there are two constraints ($\mathbf{x}'\boldsymbol{\mu} = \mu_{p,0}$ and $\mathbf{x}'\mathbf{1} = 1$) there are two Lagrange multipliers λ_1 and λ_2 . The FOCs for a minimum are the linear equations

$$\frac{\partial L(\mathbf{x}, \lambda_1, \lambda_2)}{\partial \mathbf{x}} = 2\Sigma\mathbf{x} + \lambda_1\boldsymbol{\mu} + \lambda_2\mathbf{1} = \mathbf{0}, \quad (1.15)$$

$$\frac{\partial L(\mathbf{x}, \lambda_1, \lambda_2)}{\partial \lambda_1} = \mathbf{x}'\boldsymbol{\mu} - \mu_{p,0} = 0, \quad (1.16)$$

$$\frac{\partial L(\mathbf{x}, \lambda_1, \lambda_2)}{\partial \lambda_2} = \mathbf{x}'\mathbf{1} - 1 = 0. \quad (1.17)$$

These FOCs consist of five linear equations in five unknowns ($x_A, x_B, x_C, \lambda_1, \lambda_2$). We can represent the system of linear equations using matrix algebra as

$$\begin{pmatrix} 2\Sigma & \boldsymbol{\mu} & \mathbf{1} \\ \boldsymbol{\mu}' & 0 & 0 \\ \mathbf{1}' & 0 & 0 \end{pmatrix} \begin{pmatrix} \mathbf{x} \\ \lambda_1 \\ \lambda_2 \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ \mu_{p,0} \\ 1 \end{pmatrix},$$

or

$$\mathbf{A}\mathbf{z}_x = \mathbf{b}_0,$$

where

$$\mathbf{A} = \begin{pmatrix} 2\Sigma & \boldsymbol{\mu} & \mathbf{1} \\ \boldsymbol{\mu}' & 0 & 0 \\ \mathbf{1}' & 0 & 0 \end{pmatrix}, \quad \mathbf{z}_x = \begin{pmatrix} \mathbf{x} \\ \lambda_1 \\ \lambda_2 \end{pmatrix} \quad \text{and} \quad \mathbf{b}_0 = \begin{pmatrix} \mathbf{0} \\ \mu_{p,0} \\ 1 \end{pmatrix}.$$

The solution for \mathbf{z}_x is then

$$\mathbf{z}_x = \mathbf{A}^{-1}\mathbf{b}_0. \quad (1.18)$$

The first three elements of \mathbf{z}_x are the portfolio weights $\mathbf{x} = (x_A, x_B, x_C)'$ for the minimum variance portfolio with expected return $\mu_{p,x} = \mu_{p,0}$. If $\mu_{p,0}$ is greater than or equal to the expected return on the global minimum variance portfolio then \mathbf{x} is an efficient portfolio.

Example 6 *Efficient portfolio with the same expected return as Microsoft*

Using the data in Table 1, consider finding a minimum variance portfolio with the same expected return as Microsoft. This will be an efficient portfolio because $\mu_{msft} = 0.0427 > \mu_{p,m} = 0.02489$. Call this portfolio $\mathbf{x} = (x_{msft}, x_{nord}, x_{sbux})'$. That is, consider solving (1.14) with target expected return $\mu_{p,0} = \mu_{msft} = 0.0427$ using (1.18). The R calculations to create the matrix \mathbf{A} and the vectors \mathbf{z}_x and \mathbf{b}_{msft} are:

```
> top.mat = cbind(2*sigma.mat, mu.vec, rep(1, 3))
> mid.vec = c(mu.vec, 0, 0)
> bot.vec = c(rep(1, 3), 0, 0)
> A.mat = rbind(top.mat, mid.vec, bot.vec)
> bmsft.vec = c(rep(0, 3), mu.vec["MSFT"], 1)
```

and the R code to solve for \mathbf{x} using (1.18) is:

```
> z.mat = solve(A.mat)%*%bmsft.vec
> x.vec = z.mat[1:3,]
> x.vec
      MSFT      NORD      SBUX
0.82745 -0.09075  0.26329
```

The efficient portfolio with the same expected return as Microsoft has portfolio weights $x_{msft} = 0.82745$, $x_{nord} = -0.09075$ and $x_{sbux} = 0.26329$, and is given by the vector

$$\mathbf{x} = (0.82745, -0.09075, 0.26329)'. \quad (1.19)$$

The expected return on this portfolio, $\mu_{p,x} = \mathbf{x}'\boldsymbol{\mu}$, is equal to the target return μ_{msft} :

```
> mu.px = as.numeric(crossprod(x.vec, mu.vec))
> mu.px
[1] 0.0427
```

The portfolio variance, $\sigma_{p,x}^2 = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x}$, and standard deviation, $\sigma_{p,x}$, are

```
> sig2.px = as.numeric(t(x.vec)%*%sigma.mat)%*%x.vec)
> sig.px = sqrt(sig2.px)
> sig2.px
[1] 0.0084
> sig.px
[1] 0.09166
```

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and are smaller than the corresponding values for Microsoft (see Table 1). This efficient portfolio is labeled “E1” in Figure 1.1. ■

Example 7 *Efficient portfolio with the same expected return as Microsoft*

To find a minimum variance portfolio $\mathbf{y} = (y_{msft}, y_{nord}, y_{sbux})'$ with the same expected return as Starbucks we use (1.18) with $\mathbf{b}_{sbux} = (\mathbf{0}, \mu_{sbux}, 1)'$:

```
> bsbux.vec = c(rep(0, 3), mu.vec["SBUX"], 1)
> z.mat = solve(Ax.mat)%*%bsbux.vec
> y.vec = z.mat[1:3,]
> y.vec
  MSFT  NORD  SBUX
0.5194 0.2732 0.2075
```

The portfolio

$$\mathbf{y} = (0.5194, 0.2732, 0.2075)', \quad (1.20)$$

is an efficient portfolio because $\mu_{sbux} = 0.0285 > \mu_{p,m} = 0.02489$. The portfolio expected return and standard deviation are:

```
> mu.py = as.numeric(crossprod(y.vec, mu.vec))
> sig2.py = as.numeric(t(y.vec)%*%sigma.mat%*%y.vec)
> sig.py = sqrt(sig2.py)
> mu.py
[1] 0.0285
> sig.py
[1] 0.07355
```

This efficient portfolio is labeled “E2” in Figure 1.1. It has the same expected return as SBUX but a smaller standard deviation.

The covariance and correlation values between the portfolio returns $R_{p,x} = \mathbf{x}'\mathbf{R}$ and $R_{p,y} = \mathbf{y}'\mathbf{R}$ are given by:

```
> sigma.xy = as.numeric(t(x.vec)%*%sigma.mat%*%y.vec)
> rho.xy = sigma.xy/(sig.px*sig.py)
> sigma.xy
[1] 0.005914
> rho.xy
[1] 0.8772
```

This covariance will be used later on when constructing the frontier of efficient portfolios.

■

Alternative derivation of efficient portfolio

Consider the first order conditions (1.15)-(1.17) from the optimization problem (1.14). First, use (1.15) to solve for the 3×1 vector \mathbf{x} :

$$\mathbf{x} = -\frac{1}{2}\lambda_1\boldsymbol{\Sigma}^{-1}\boldsymbol{\mu} - \frac{1}{2}\lambda_2\boldsymbol{\Sigma}^{-1}\mathbf{1}. \quad (1.21)$$

Define the 3×2 matrix $\mathbf{M} = [\boldsymbol{\mu} \ : \ \mathbf{1}]$ and the 2×1 vector $\boldsymbol{\lambda} = (\lambda_1, \lambda_2)'$. Then we can rewrite (1.21) in matrix form as

$$\mathbf{x} = -\frac{1}{2}\boldsymbol{\Sigma}^{-1}\mathbf{M}\boldsymbol{\lambda}. \quad (1.22)$$

Next, to find the values for λ_1 and λ_2 , pre-multiply (1.21) by $\boldsymbol{\mu}'$ and use (1.16) to give

$$\mu_0 = \boldsymbol{\mu}'\mathbf{x} = -\frac{1}{2}\lambda_1\boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\boldsymbol{\mu} - \frac{1}{2}\lambda_2\boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\mathbf{1}. \quad (1.23)$$

Similarly, pre-multiply (1.21) by $\mathbf{1}'$ and use (1.17) to give

$$1 = \mathbf{1}'\mathbf{x} = -\frac{1}{2}\lambda_1\mathbf{1}'\boldsymbol{\Sigma}^{-1}\boldsymbol{\mu} - \frac{1}{2}\lambda_2\mathbf{1}'\boldsymbol{\Sigma}^{-1}\mathbf{1}. \quad (1.24)$$

Now, we have two linear equations (1.23) and (1.24) involving λ_1 and λ_2 which we can write in matrix notation as

$$-\frac{1}{2} \begin{pmatrix} \boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\boldsymbol{\mu} & \boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\mathbf{1} \\ \boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\mathbf{1} & \mathbf{1}'\boldsymbol{\Sigma}^{-1}\mathbf{1} \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix} = \begin{pmatrix} \mu_0 \\ 1 \end{pmatrix}. \quad (1.25)$$

Define

$$\begin{pmatrix} \boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\boldsymbol{\mu} & \boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\mathbf{1} \\ \boldsymbol{\mu}'\boldsymbol{\Sigma}^{-1}\mathbf{1} & \mathbf{1}'\boldsymbol{\Sigma}^{-1}\mathbf{1} \end{pmatrix} = \mathbf{M}'\boldsymbol{\Sigma}^{-1}\mathbf{M} = \mathbf{B},$$

$$\tilde{\boldsymbol{\mu}}_0 = \begin{pmatrix} \mu_0 \\ 1 \end{pmatrix},$$

so that we can rewrite (1.25) as

$$-\frac{1}{2}\mathbf{B}\boldsymbol{\lambda} = \tilde{\boldsymbol{\mu}}_0. \quad (1.26)$$

The solution for $\boldsymbol{\lambda} = (\lambda_1, \lambda_2)'$ is then

$$\boldsymbol{\lambda} = -2\mathbf{B}^{-1}\tilde{\boldsymbol{\mu}}_0. \quad (1.27)$$

Substituting (1.27) back into (1.22) gives an explicit expression for the efficient portfolio weight vector \mathbf{x} :

$$\mathbf{x} = -\frac{1}{2}\Sigma^{-1}\mathbf{M}\boldsymbol{\lambda} = -\frac{1}{2}\Sigma^{-1}\mathbf{M}(-2\mathbf{B}^{-1}\tilde{\boldsymbol{\mu}}_0) = \Sigma^{-1}\mathbf{M}\mathbf{B}^{-1}\tilde{\boldsymbol{\mu}}_0. \quad (1.28)$$

Example 8 *Alternative solution for efficient portfolio with the same expected return as Microsoft*

The R code to compute the efficient portfolio with the same expected return as Microsoft using (1.28) is:

```
> M.mat = cbind(mu.vec, one.vec)
> B.mat = t(M.mat)%*%solve(sigma.mat)%*%M.mat
> mu.tilde.msft = c(mu.vec["MSFT"], 1)
> x.vec.2 = solve(sigma.mat)%*%M.mat%*%solve(B.mat)%*%mu.tilde.msft
> x.vec.2
      [,1]
MSFT  0.82745
NORD -0.09075
SBUX  0.26329
```

■

1.1.4 Computing the Efficient Frontier

The analytic expression for a minimum variance portfolio (1.28) can be used to show that any minimum variance portfolio can be created as a convex combination of any two minimum variance portfolios with different target expected returns. If the expected return on the resulting portfolio is greater than the expected on the global minimum variance portfolio, then the portfolio is an efficient frontier portfolio. Otherwise, the portfolio is an inefficient frontier portfolio. As a result, to compute the portfolio frontier in (μ_p, σ_p) space (Markowitz bullet) we only need to find two efficient portfolios. The remaining frontier portfolios can then be expressed as convex combinations of these two portfolios. The following proposition describes the process for the three risky asset case using matrix algebra.

Proposition 9 *Creating a frontier portfolio from two efficient portfolios*

Let $\mathbf{x} = (x_A, x_B, x_C)'$ and $\mathbf{y} = (y_A, y_B, y_C)'$ be any two minimum variance portfolios with different target expected returns $\mathbf{x}'\boldsymbol{\mu} = \mu_{p,0} \neq \mathbf{y}'\boldsymbol{\mu} = \mu_{p,1}$. That is, portfolio \mathbf{x} solves

$$\min_{\mathbf{x}} \sigma_{p,x}^2 = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x} \quad s.t. \quad \mathbf{x}'\boldsymbol{\mu} = \mu_{p,0} \quad \text{and} \quad \mathbf{x}'\mathbf{1} = 1,$$

and portfolio \mathbf{y} solves

$$\min_{\mathbf{y}} \sigma_{p,y}^2 = \mathbf{y}'\boldsymbol{\Sigma}\mathbf{y} \quad s.t. \quad \mathbf{y}'\boldsymbol{\mu} = \mu_{p,1} \quad \text{and} \quad \mathbf{y}'\mathbf{1} = 1.$$

Let α be any constant and define the portfolio \mathbf{z} as a linear combination of portfolios \mathbf{x} and \mathbf{y} :

$$\begin{aligned} \mathbf{z} &= \alpha \cdot \mathbf{x} + (1 - \alpha) \cdot \mathbf{y} \\ &= \begin{pmatrix} \alpha x_A + (1 - \alpha)y_A \\ \alpha x_B + (1 - \alpha)y_B \\ \alpha x_C + (1 - \alpha)y_C \end{pmatrix}, \end{aligned} \tag{1.29}$$

Then

(a) The portfolio \mathbf{z} is a minimum variance portfolio with expected return and variance given by

$$\mu_{p,z} = \mathbf{z}'\boldsymbol{\mu} = \alpha \cdot \mu_{p,x} + (1 - \alpha) \cdot \mu_{p,y}, \tag{1.30}$$

$$\sigma_{p,z}^2 = \mathbf{z}'\boldsymbol{\Sigma}\mathbf{z} = \alpha^2 \sigma_{p,x}^2 + (1 - \alpha)^2 \sigma_{p,y}^2 + 2\alpha(1 - \alpha)\sigma_{xy}, \tag{1.31}$$

where

$$\sigma_{p,x}^2 = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x}, \sigma_{p,y}^2 = \mathbf{y}'\boldsymbol{\Sigma}\mathbf{y}, \sigma_{xy} = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{y}.$$

(b) If $\mu_{p,z} \geq \mu_{p,m}$, where $\mu_{p,m}$ is the expected return on the global minimum variance portfolio, then portfolio \mathbf{z} is an efficient portfolio. Otherwise, \mathbf{z} is an inefficient frontier portfolio.

The proof of (a) follows directly from applying (1.28) to portfolios \mathbf{x} and \mathbf{y} :

$$\begin{aligned} \mathbf{x} &= \boldsymbol{\Sigma}^{-1}\mathbf{M}\mathbf{B}^{-1}\tilde{\boldsymbol{\mu}}_x, \\ \mathbf{y} &= \boldsymbol{\Sigma}^{-1}\mathbf{M}\mathbf{B}^{-1}\tilde{\boldsymbol{\mu}}_y, \end{aligned}$$

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where $\tilde{\boldsymbol{\mu}}_x = (\mu_{p,x}, 1)'$ and $\tilde{\boldsymbol{\mu}}_y = (\mu_{p,y}, 1)'$. Then for portfolio \mathbf{z}

$$\begin{aligned}\mathbf{z} &= \alpha \cdot \mathbf{x} + (1 - \alpha) \cdot \mathbf{y} \\ &= \alpha \cdot \Sigma^{-1} \mathbf{M} \mathbf{B}^{-1} \tilde{\boldsymbol{\mu}}_x + (1 - \alpha) \cdot \Sigma^{-1} \mathbf{M} \mathbf{B}^{-1} \tilde{\boldsymbol{\mu}}_y \\ &= \Sigma^{-1} \mathbf{M} \mathbf{B}^{-1} (\alpha \cdot \tilde{\boldsymbol{\mu}}_x + (1 - \alpha) \cdot \tilde{\boldsymbol{\mu}}_y) \\ &= \Sigma^{-1} \mathbf{M} \mathbf{B}^{-1} \tilde{\boldsymbol{\mu}}_z,\end{aligned}$$

where $\tilde{\boldsymbol{\mu}}_z = \alpha \cdot \tilde{\boldsymbol{\mu}}_x + (1 - \alpha) \cdot \tilde{\boldsymbol{\mu}}_y = (\mu_{p,z}, 1)'$.

Example 10 *Creating an arbitrary frontier portfolio from two efficient portfolios*

Consider the data in Table 1 and the previously computed efficient portfolios (1.19) and (1.20) and let $\alpha = 0.5$. From (1.29), the frontier portfolio \mathbf{z} is constructed using

$$\begin{aligned}\mathbf{z} &= \alpha \cdot \mathbf{x} + (1 - \alpha) \cdot \mathbf{y} \\ &= 0.5 \cdot \begin{pmatrix} 0.82745 \\ -0.09075 \\ 0.26329 \end{pmatrix} + 0.5 \cdot \begin{pmatrix} 0.5194 \\ 0.2732 \\ 0.2075 \end{pmatrix} \\ &= \begin{pmatrix} (0.5)(0.82745) \\ (0.5)(-0.09075) \\ (0.5)(0.26329) \end{pmatrix} + \begin{pmatrix} (0.5)(0.5194) \\ (0.5)(0.2732) \\ (0.5)(0.2075) \end{pmatrix} \\ &= \begin{pmatrix} 0.6734 \\ 0.0912 \\ 0.2354 \end{pmatrix} = \begin{pmatrix} z_A \\ z_B \\ z_C \end{pmatrix}.\end{aligned}$$

In R, the new frontier portfolio is computed using

```
> a = 0.5
> z.vec = a*x.vec + (1-a)*y.vec
> z.vec
  MSFT  NORD  SBUX
0.6734 0.0912 0.2354
```

Using $\mu_{p,z} = \mathbf{z}'\boldsymbol{\mu}$ and $\sigma_{p,z}^2 = \mathbf{z}'\boldsymbol{\Sigma}\mathbf{z}$, the expected return, variance and standard deviation of this portfolio are

```
> mu.pz = as.numeric(crossprod(z.vec, mu.vec))
> sig2.pz = as.numeric(t(z.vec)%*%sigma.mat%*%z.vec)
> sig.pz = sqrt(sig2.pz)
> mu.pz
[1] 0.0356
> sig2.pz
[1] 0.00641
> sig.pz
[1] 0.08006
```

Equivalently, using $\mu_{p,z} = \alpha\mu_{p,x} + (1-\alpha)\mu_{p,y}$ and $\sigma_{p,z}^2 = \alpha^2\sigma_{p,x}^2 + (1-\alpha)^2\sigma_{p,y}^2 + 2\alpha(1-\alpha)\sigma_{xy}$ the expected return, variance and standard deviation of this portfolio are

```
> mu.pz = a*mu.px + (1-a)*mu.py
> sig.xy = as.numeric(t(x.vec)%*%sigma.mat%*%y.vec)
> sig2.pz = a^2 * sig2.px + (1-a)^2 * sig2.py + 2*a*(1-a)*sig.xy
> sig.pz = sqrt(sig2.pz)
> mu.pz
[1] 0.0356
> sig2.pz
[1] 0.00641
> sig.pz
[1] 0.08006
```

Because $\mu_{p,z} = 0.0356 > \mu_{p,m} = 0.02489$ the frontier portfolio \mathbf{z} is an efficient portfolio. The three efficient portfolios \mathbf{x} , \mathbf{y} and \mathbf{z} are illustrated in Figure 1.2 and are labeled “E1”, “E2” and “E3”, respectively. ■

Example 11 *Creating a frontier portfolio with a given expected return from two efficient portfolios*

Given the two efficient portfolios (1.19) and (1.20) with target expected returns equal to the expected returns on Microsoft and Starbucks, respectively, consider creating a frontier portfolio with target expected return equal to the expected return on Nordstrom. Then

$$\mu_{p,z} = \alpha\mu_{p,x} + (1-\alpha)\mu_{p,y} = \mu_{nord} = 0.0015,$$

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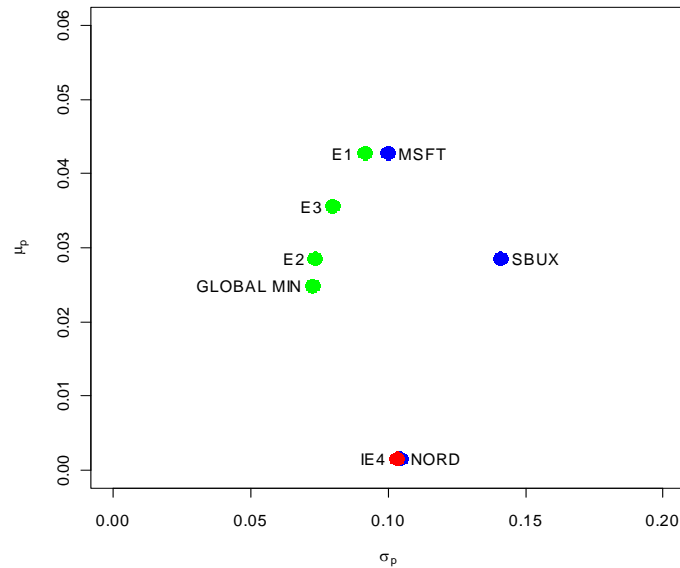


Figure 1.2: Three efficient portfolios of Microsoft, Nordstrom and Starbucks.

and we can solve for α using

$$\alpha = \frac{\mu_{nord} - \mu_{p,y}}{\mu_{p,x} - \mu_{p,y}} = \frac{0.0015 - 0.0285}{0.0427 - 0.0285} = -1.901.$$

Using R, the weights in this frontier portfolio are

```
> a.nord = (mu.vec["NORD"] - mu.py)/(mu.px - mu.py)
> z.nord = a.nord*x.vec + (1 - a.nord)*y.vec
> z.nord
      MSFT      NORD      SBUX
-0.06637  0.96509  0.10128
```

The expected return, variance and standard deviation on this portfolio are

```
> mu.pz.nord = a.nord*mu.px + (1-a.nord)*mu.py
> sig2.pz.nord = a.nord^2 * sig2.px + (1-a.nord)^2 * sig2.py +
+               2*a.nord*(1-a.nord)*sigma.xy
```

```

> sig.pz.nord = sqrt(sig2.pz.nord)
> mu.pz.nord
  NORD
0.0015
> sig2.pz.nord
  NORD
0.01066
> sig.pz.nord
  NORD
0.1033

```

Because $\mu_{p,z} = 0.0015 < \mu_{p,m} = 0.02489$ the frontier portfolio \mathbf{z} is an inefficient frontier portfolio. This portfolio is labeled “IE4” in Figure 1.2. ■

The efficient frontier of portfolios, i.e., those frontier portfolios with expected return greater than the expected return on the global minimum variance portfolio, can be conveniently created using (1.29) with two specific efficient portfolios. The first efficient portfolio is the global minimum variance portfolio (1.4). The second efficient portfolio is the efficient portfolio whose target expected return is equal to the highest expected return among all of the assets under consideration. The steps for constructing the efficient frontier are:

1. Compute the global minimum variance portfolio \mathbf{m} by solving (1.6), and compute $\mu_{p,m} = \mathbf{m}'\boldsymbol{\mu}$ and $\sigma_{p,m}^2 = \mathbf{m}'\boldsymbol{\Sigma}\mathbf{m}$.
2. Compute the efficient portfolio \mathbf{x} by with target expected return equal to the maximum expected return of the assets under consideration. That is, solve (1.14) with $\mu_0 = \max\{\mu_1, \mu_2, \mu_3\}$, and compute $\mu_{p,x} = \mathbf{x}'\boldsymbol{\mu}$ and $\sigma_{p,m}^2 = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x}$.
3. Compute $\text{cov}(R_{p,m}, R_{p,x}) = \sigma_{mx} = \mathbf{m}'\boldsymbol{\Sigma}\mathbf{x}$.
4. Create an initial grid of α values $\{1, 0.9, \dots, -0.9, -1\}$, compute the frontier portfolios \mathbf{z} using (1.29), and compute their expected returns and variances using (1.29), (1.30) and (1.31), respectively.
5. Plot $\mu_{p,z}$ against $\sigma_{p,z}$ and adjust the grid of α values to create a nice plot.

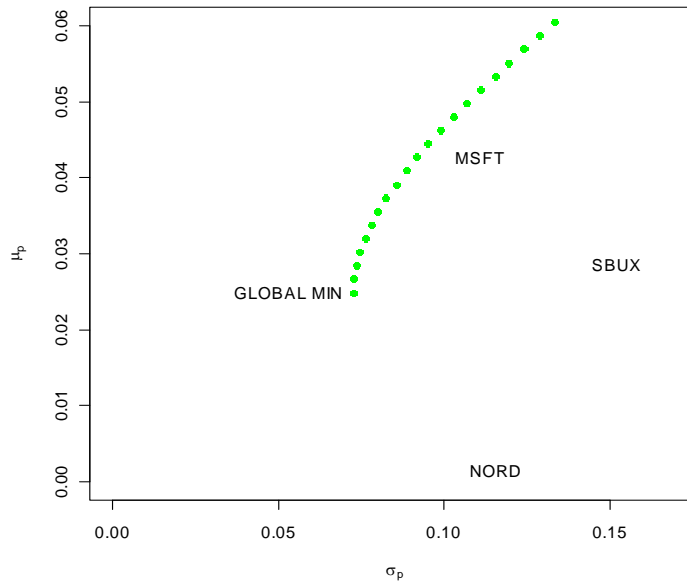


Figure 1.3: Efficient frontier of three risky assets.

Example 12 *Compute and plot the efficient frontier of risky assets (Markowitz bullet)*

To compute and plot the efficient frontier from the three risky assets in Table 1.1 in R use

```
> a = seq(from=1, to=-1, by=-0.1)
> n.a = length(a)
> z.mat = matrix(0, n.a, 3)
> mu.z = rep(0, n.a)
> sig2.z = rep(0, n.a)
> sig.mx = t(m)%%sigma.mat%%x.vec
> for (i in 1:n.a) {
+   z.mat[i, ] = a[i]*m + (1-a[i])*x.vec
+   mu.z[i] = a[i]*mu.gmin + (1-a[i])*mu.px
+   sig2.z[i] = a[i]^2 * sig2.gmin + (1-a[i])^2 * sig2.px +
+             2*a[i]*(1-a[i])*sig.mx
}
```

```

+ }
> plot(sqrt(sig2.z), mu.z, type="b", ylim=c(0, 0.06), xlim=c(0, 0.17),
+       pch=16, col="blue", ylab=expression(mu[p]),
+       xlab=expression(sigma[p]))
> text(sig.gmin, mu.gmin, labels="Global min", pos=4)
> text(sd.vec, mu.vec, labels=asset.names, pos=4)

```

The variables `z.mat`, `mu.z` and `sig2.z` contain the weights, expected returns and variances, respectively, of the efficient frontier portfolios for a grid of α values between 1 and -1 . The resulting efficient frontier is illustrated in Figure 1.3. ■

1.1.5 Efficient Portfolios of Three Risky Assets and a Risk-Free Asset

In the previous chapter, we showed that efficient portfolios of two risky assets and a single risk-free (T-Bill) asset are portfolios consisting of the highest Sharpe ratio portfolio (tangency portfolio) and the T-Bill. With three or more risky assets and a T-Bill the same result holds.

Computing the Tangency Portfolio

The tangency portfolio is the portfolio of risky assets that has the highest Sharpe ratio. The tangency portfolio, denoted $\mathbf{t} = (t_{msft}, t_{nord}, t_{sbux})'$, solves the constrained maximization problem

$$\max_{\mathbf{t}} \frac{\mathbf{t}'\boldsymbol{\mu} - r_f}{(\mathbf{t}'\boldsymbol{\Sigma}\mathbf{t})^{\frac{1}{2}}} = \frac{\mu_{p,t} - r_f}{\sigma_{p,t}} \text{ s.t. } \mathbf{t}'\mathbf{1} = 1.$$

where $\mu_{p,t} = \mathbf{t}'\boldsymbol{\mu}$ and $\sigma_{p,t} = (\mathbf{t}'\boldsymbol{\Sigma}\mathbf{t})^{\frac{1}{2}}$. The Lagrangian for this problem is

$$L(\mathbf{t}, \lambda) = (\mathbf{t}'\boldsymbol{\mu} - r_f) (\mathbf{t}'\boldsymbol{\Sigma}\mathbf{t})^{-\frac{1}{2}} + \lambda(\mathbf{t}'\mathbf{1} - 1)$$

Using the chain rule, the first order conditions are

$$\begin{aligned} \frac{\partial L(\mathbf{t}, \lambda)}{\partial \mathbf{t}} &= \boldsymbol{\mu}(\mathbf{t}'\boldsymbol{\Sigma}\mathbf{t})^{-\frac{1}{2}} - (\mathbf{t}'\boldsymbol{\mu} - r_f) (\mathbf{t}'\boldsymbol{\Sigma}\mathbf{t})^{-3/2}\boldsymbol{\Sigma}\mathbf{t} + \lambda\mathbf{1} = \mathbf{0} \\ \frac{\partial L(\mathbf{t}, \lambda)}{\partial \lambda} &= \mathbf{t}'\mathbf{1} - 1 = 0 \end{aligned}$$

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After much tedious algebra, it can be shown that the solution for \mathbf{t} has a nice simple expression:

$$\mathbf{t} = \frac{\boldsymbol{\Sigma}^{-1}(\boldsymbol{\mu} - r_f \cdot \mathbf{1})}{\mathbf{1}'\boldsymbol{\Sigma}^{-1}(\boldsymbol{\mu} - r_f \cdot \mathbf{1})}. \quad (1.32)$$

The location of the tangency portfolio, and the sign of the Sharpe ratio, depends on the relationship between the risk-free rate r_f and the expected return on the global minimum variance portfolio $\mu_{p,m}$. If $\mu_{p,m} > r_f$, which is the usual case, then the tangency portfolio will have a positive Sharpe ratio. If $\mu_{p,m} < r_f$, which could occur when stock prices are falling and the economy is in a recession, then the tangency portfolio will have a negative Sharpe slope. In this case, efficient portfolios involve shorting the tangency portfolio and investing the proceeds in T-Bills.

Example 13 *Computing the tangency portfolio*

Suppose $r_f = 0.005$. To compute the tangency portfolio (1.32) in R for the three risky assets in Table use

```
> rf = 0.005
> sigma.inv.mat = solve(sigma.mat)
> one.vec = rep(1, 3)
> mu.minus.rf = mu.vec - rf*one.vec
> top.mat = sigma.inv.mat%%mu.minus.rf
> bot.val = as.numeric(t(one.vec)%*%top.mat)
> t.vec = top.mat[,1]/bot.val
> t.vec
      MSFT      NORD      SBUX
1.0268 -0.3263  0.2994
```

The tangency portfolio has weights $t_{msft} = 1.0268$, $t_{nord} = -0.3263$ and $t_{sbux} = 0.2994$, and is given by the vector

$$\mathbf{t} = (1.0268, -0.3263, 0.2994)'. \quad (1.33)$$

Notice that Nordstrom, which has the lowest mean return, is sold short in the tangency portfolio. The expected return on the tangency portfolio, $\mu_{p,t} = \mathbf{t}'\boldsymbol{\mu}$, is


```
> mu.t = as.numeric(crossprod(t.vec, mu.vec))
> mu.t
[1] 0.05189
```

The portfolio variance, $\sigma_{p,t}^2 = \mathbf{t}'\Sigma\mathbf{t}$, and standard deviation, $\sigma_{p,t}$, are

```
> sig2.t = as.numeric(t(t.vec)%*%sigma.mat%*%t.vec)
> sig.t = sqrt(sig2.t)
> sig2.t
[1] 0.01245
> sig.t
[1] 0.1116
```

Because $r_f = 0.005 < \mu_{p,m} = 0.02489$ the tangency portfolio has a positive Sharpe's ratio/slope given by

$$SR_t = \frac{\mu_{p,t} - r_f}{\sigma_{p,t}} = \frac{0.05189 - 0.005}{0.1116} = 0.4202.$$

■

Alternative Derivation of the Tangency Portfolio

Consider forming portfolios of three risky assets with return vector \mathbf{R} and T-bills (risk-free asset) with constant return r_f . Let x denote the vector of risky asset weights and let x_f denote the safe asset weight and assume that $\mathbf{x}'\mathbf{1} + x_f = 1$ so that all wealth is allocated to these assets. The portfolio return is

$$R_{p,x} = \mathbf{x}'\mathbf{R} + x_f r_f = \mathbf{x}'\mathbf{R} + (1 - \mathbf{x}'\mathbf{1})r_f = r_f + \mathbf{x}'(\mathbf{R} - r_f \cdot \mathbf{1}).$$

The portfolio excess return is

$$R_{p,x} - r_f = \mathbf{x}'(\mathbf{R} - r_f \cdot \mathbf{1}). \quad (1.34)$$

The expected portfolio return excess return (risk premium) and portfolio variance are

$$\mu_{p,x} - r_f = \mathbf{x}'(\boldsymbol{\mu} - r_f \cdot \mathbf{1}), \quad (1.35)$$

$$\sigma_{p,x}^2 = \mathbf{x}'\Sigma\mathbf{x}. \quad (1.36)$$

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For notational simplicity, define $\tilde{\mathbf{R}} = \mathbf{R} - r_f \cdot \mathbf{1}$, $\tilde{\boldsymbol{\mu}} = \boldsymbol{\mu} - r_f \cdot \mathbf{1}$, $\tilde{R}_{p,x} = R_{p,x} - r_f$, and $\tilde{\mu}_{p,x} = \mu_{p,x} - r_f$. Then (1.34) and (1.35) can be re-expressed as

$$\tilde{R}_{p,x} = \mathbf{x}'\tilde{\mathbf{R}}, \quad (1.37)$$

$$\tilde{\mu}_{p,x} = \mathbf{x}'\tilde{\boldsymbol{\mu}}. \quad (1.38)$$

To find the minimum variance portfolio of risky assets and a risk free asset that achieves the target excess return $\tilde{\mu}_{p,0} = \mu_{p,0} - r_f$ we solve the minimization problem

$$\min_{\mathbf{x}} \sigma_{p,x}^2 = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x} \text{ s.t. } \tilde{\mu}_{p,x} = \tilde{\mu}_{p,0}.$$

Note that $\mathbf{x}'\mathbf{1} = 1$ is not a constraint because wealth need not all be allocated to the risky assets; some wealth may be held in the riskless asset. The Lagrangian is

$$L(\mathbf{x}, \lambda) = \mathbf{x}'\boldsymbol{\Sigma}\mathbf{x} + \lambda(\mathbf{x}'\tilde{\boldsymbol{\mu}} - \tilde{\mu}_{p,0}).$$

The first order conditions for a minimum are

$$\frac{\partial L(\mathbf{x}, \lambda)}{\partial \mathbf{x}} = 2\boldsymbol{\Sigma}\mathbf{x} + \lambda\tilde{\boldsymbol{\mu}} = \mathbf{0}, \quad (1.39)$$

$$\frac{\partial L(\mathbf{x}, \lambda)}{\partial \lambda} = \mathbf{x}'\tilde{\boldsymbol{\mu}} - \tilde{\mu}_{p,0} = 0. \quad (1.40)$$

Using the first equation (1.39), we can solve for \mathbf{x} in terms of λ :

$$\mathbf{x} = -\frac{1}{2}\lambda\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}}. \quad (1.41)$$

The second equation (1.40) implies that $\mathbf{x}'\tilde{\boldsymbol{\mu}} = \tilde{\boldsymbol{\mu}}'\mathbf{x} = \tilde{\mu}_{p,0}$. Then premultiplying (1.41) by $\tilde{\boldsymbol{\mu}}'$ gives

$$\tilde{\boldsymbol{\mu}}'\mathbf{x} = -\frac{1}{2}\lambda\tilde{\boldsymbol{\mu}}'\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}} = \tilde{\mu}_{p,0},$$

which we can use to solve for λ :

$$\lambda = -\frac{2\tilde{\mu}_{p,0}}{\tilde{\boldsymbol{\mu}}'\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}}}. \quad (1.42)$$

Plugging (1.42) into (1.41) then gives the solution for \mathbf{x} :

$$\mathbf{x} = -\frac{1}{2}\lambda\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}} = -\frac{1}{2}\left(-\frac{2\tilde{\mu}_{p,0}}{\tilde{\boldsymbol{\mu}}'\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}}}\right)\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}} = \tilde{\mu}_{p,0} \cdot \frac{\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}}}{\tilde{\boldsymbol{\mu}}'\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{\mu}}}. \quad (1.43)$$

The solution for x_f is then $1 - \mathbf{x}'\mathbf{1}$.

Now, the tangency portfolio \mathbf{t} is 100% invested in risky assets so that $\mathbf{t}'\mathbf{1} = \mathbf{1}'\mathbf{t} = 1$. Using (1.43), the tangency portfolio satisfies

$$\mathbf{1}'\mathbf{t} = \tilde{\mu}_{p,t} \cdot \frac{\mathbf{1}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}}{\tilde{\boldsymbol{\mu}}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}} = 1,$$

which implies that

$$\tilde{\mu}_{p,t} = \frac{\tilde{\boldsymbol{\mu}}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}}{\mathbf{1}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}}. \quad (1.44)$$

Plugging (1.44) back into (1.43) then gives an explicit solution for \mathbf{t} :

$$\begin{aligned} \mathbf{t} &= \left(\frac{\tilde{\boldsymbol{\mu}}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}}{\mathbf{1}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}} \right) \frac{\Sigma^{-1}\tilde{\boldsymbol{\mu}}}{\tilde{\boldsymbol{\mu}}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}} = \frac{\Sigma^{-1}\tilde{\boldsymbol{\mu}}}{\mathbf{1}'\Sigma^{-1}\tilde{\boldsymbol{\mu}}} \\ &= \frac{\Sigma^{-1}(\boldsymbol{\mu} - r_f \cdot \mathbf{1})}{\mathbf{1}'\Sigma^{-1}(\boldsymbol{\mu} - r_f \cdot \mathbf{1})}, \end{aligned}$$

which is the result (1.32) we got from finding the portfolio of risky assets that has the maximum Sharpe ratio.

1.1.6 Mutual Fund Separation Theorem Again

When there is a risk-free asset (T-bill) available, the efficient frontier of T-bills and risky assets consists of portfolios of T-bills and the tangency portfolio. The expected return and standard deviation values of any such efficient portfolio are given by

$$\mu_p^e = r_f + x_t(\mu_{p,t} - r_f), \quad (1.45)$$

$$\sigma_p^e = x_t\sigma_{p,t}, \quad (1.46)$$

where x_t represents the fraction of wealth invested in the tangency portfolio ($1 - x_t$ represents the fraction of wealth invested in T-Bills), and $\mu_{p,t} = \mathbf{t}'\boldsymbol{\mu}$ and $\sigma_{p,t} = (\mathbf{t}'\Sigma\mathbf{t})^{1/2}$ are the expected return and standard deviation on the tangency portfolio, respectively. Recall, this result is known as the *mutual fund separation theorem*. The tangency portfolio can be considered as a mutual fund of the risky assets, where the shares of the assets in the mutual fund are determined by the tangency portfolio weights, and the T-bill can be considered as a mutual fund of risk-free assets. The expected return-risk

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trade-off of these portfolios is given by the line connecting the risk-free rate to the tangency point on the efficient frontier of risky asset only portfolios. Which combination of the tangency portfolio and the T-bill an investor will choose depends on the investor's risk preferences. If the investor is very risk averse and prefers portfolios with very low volatility, then she will choose a combination with very little weight in the tangency portfolio and a lot of weight in the T-bill. This will produce a portfolio with an expected return close to the risk-free rate and a variance that is close to zero. If the investor can tolerate a large amount of volatility, then she will prefer a portfolio with a high expected return regardless of volatility. This portfolio may involve borrowing at the risk-free rate (leveraging) and investing the proceeds in the tangency portfolio to achieve a high expected return.

Example 14 *Efficient portfolios of three risky assets and T-bills chosen by risk averse and risk tolerant investors*

Consider the tangency portfolio computed from the example data in Table 1.1 with $r_f = 0.005$. This portfolio is

```
> t.vec
      MSFT      NORD      SBUX
1.0268 -0.3263  0.2994
> mu.t
[1] 0.05189
> sig.t
[1] 0.1116
```

The efficient portfolios of T-Bills and the tangency portfolio is illustrated in Figure .

We want to compute an efficient portfolio that would be preferred by a highly risk averse investor, and a portfolio that would be preferred by a highly risk tolerant investor. A highly risk averse investor might have a low volatility (risk) target for his efficient portfolio. For example, suppose the volatility target is $\sigma_p^e = 0.02$ or 2%. Using (1.46) and solving for x_t , the weights in the tangency portfolio and the T-Bill are

```
> x.t.02 = 0.02/sig.t
> x.t.02
[1] 0.1792
> 1-x.t.02
[1] 0.8208
```

In this efficient portfolio, the weights in the risky assets are proportional to the weights in the tangency portfolio

```
> x.t.02*t.vec
      MSFT      NORD      SBUX
0.18405 -0.05848  0.05367
```

The expected return and volatility values of this portfolio are

```
> mu.t.02 = x.t.02*mu.t + (1-x.t.02)*rf
> sig.t.02 = x.t.02*sig.t
> mu.t.02
[1] 0.01340
> sig.t.02
[1] 0.02
```

These values are illustrated in Figure as the portfolio labeled “E1”.

A highly risk tolerant investor might have a high expected return target for his efficient portfolio. For example, suppose the expected return target is $\mu_p^e = 0.07$ or 7%. Using (1.45) and solving for the x_t , the weights in the tangency portfolio and the T-Bill are

```
> x.t.07 = (0.07 - rf)/(mu.t - rf)
> x.t.07
[1] 1.386
> 1-x.t.07
[1] -0.3862
```

Notice that this portfolio involves borrowing at the T-Bill rate (leveraging) and investing the proceeds in the tangency portfolio. In this efficient portfolio, the weights in the risky assets are

```
> x.t.07*t.vec
      MSFT      NORD      SBUX
1.4234 -0.4523  0.4151
```

The expected return and volatility values of this portfolio are

```
> mu.t.07 = x.t.07*mu.t + (1-x.t.07)*rf
> sig.t.07 = x.t.07*sig.t
> mu.t.07
```

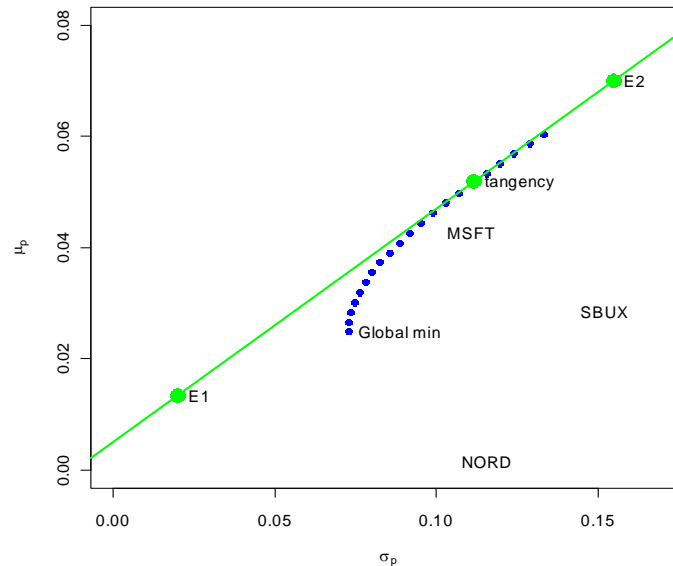


Figure 1.4: Efficient portfolios of three risky assets. The portfolio labeled “E1” is chosen by a risk averse investor with a target volatility of 0.02. The portfolio “E2” is chosen by a risk tolerant investor with a target expected return of 0.07.

```
[1] 0.07
> sig.t.07
[1] 0.1547
```

In order to achieve the target expected return of 7%, the investor must tolerate a 15.47% volatility. These values are illustrated in Figure as the portfolio labeled “E2”.

■

1.2 Portfolio Analysis Functions in R

The script file `portfolio.r` contains a few R functions for computing Markowitz mean-variance efficient portfolios allowing for short sales using matrix alge-

Function	Description
<code>getPortfolio</code>	create portfolio object
<code>globalMin.portfolio</code>	compute global minimum variance portfolio
<code>efficient.portfolio</code>	compute minimum variance portfolio subject to target return
<code>tangency.portfolio</code>	compute tangency portfolio
<code>efficient.frontier</code>	compute efficient frontier of risky assets

Table 1.2: R functions for computing mean-variance efficient portfolios

bra computations². These functions allow for the easy computation of the global minimum variance portfolio, an efficient portfolio with a given target expected return, the tangency portfolio, and the efficient frontier. These functions are summarized in Table 1.2.

The following examples illustrate the use of the functions in Table 1.2 using the example data in Table 1.1. We first construct the input data:

```
> asset.names = c("MSFT", "NORD", "SBUX")
> er = c(0.0427, 0.0015, 0.0285)
> names(er) = asset.names
> covmat = matrix(c(0.0100, 0.0018, 0.0011,
+                   0.0018, 0.0109, 0.0026,
+                   0.0011, 0.0026, 0.0199),
+                 nrow=3, ncol=3)
> rk.free = 0.005
> dimnames(covmat) = list(asset.names, asset.names)
```

To specify a portfolio object, you need an expected return vector and covariance matrix for the assets under consideration as well as a vector of portfolio weights. To create an equally weighted portfolio use

```
> ew = rep(1,3)/3
> equalWeight.portfolio = getPortfolio(er=er,cov.mat=covmat,weights=ew)
```

²To use the functions in this script file, load them into R with the `source()` function. For example, if `portfolio.r` is located in `C:\mydata` run the command `source("C:/mydata/portfolio.r")` at the beginning of your R session. Then the functions in the file will be available for your use.

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```
> class(equalWeight.portfolio)
[1] "portfolio"
```

Portfolio objects have the following components

```
> names(equalWeight.portfolio)
[1] "call"      "er"        "sd"        "weights"
```

There are `print()`, `summary()` and `plot()` methods for portfolio objects. The `print()` method gives

```
> equalWeight.portfolio
Call:
getPortfolio(er = er, cov.mat = covmat, weights = ew)
```

```
Portfolio expected return:      0.02423
Portfolio standard deviation:   0.07587
Portfolio weights:
  MSFT  NORD  SBUX
0.3333 0.3333 0.3333
```

The `plot()` method shows a bar chart of the portfolio weights

```
> plot(equalWeight.portfolio)
```

The global minimum variance portfolio (allowing for short sales) \mathbf{m} solves the optimization problem

$$\min_{\mathbf{m}} \mathbf{m}'\Sigma\mathbf{m} \text{ s.t. } \mathbf{m}'\mathbf{1} = 1.$$

To compute this portfolio use the function `globalMin.portfolio()`

```
> gmin.port <- globalMin.portfolio(er, covmat)
> attributes(gmin.port)
$names
[1] "call"      "er"        "sd"        "weights"

$class
[1] "portfolio"
> gmin.port
Call:
```

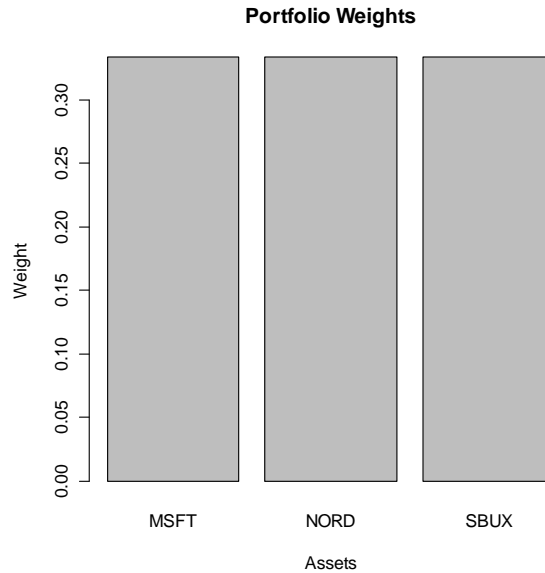



Figure 1.5:

```
globalMin.portfolio(er = er, cov.mat = covmat)
```

```
Portfolio expected return:      0.02489184
```

```
Portfolio standard deviation:  0.07267607
```

```
Portfolio weights:
```

```
  MSFT  NORD  SBUX
0.4411 0.3656 0.1933
```

A mean-variance efficient portfolio \mathbf{x} that achieves the target expected return μ_0 solves the optimization problem

$$\min_x \mathbf{x}'\Sigma\mathbf{x} \text{ s.t. } \mathbf{x}'\mathbf{1} = 1 \text{ and } \mathbf{x}'\boldsymbol{\mu} = \mu_0.$$

To compute this portfolio for the target expected return $\mu_0 = E[R_{msft}] = 0.04275$ use the `efficient.portfolio()` function

```
> target.return <- er[1]
> e.port.msft <- efficient.portfolio(er, covmat, target.return)
> e.port.msft
```

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Call:

```
efficient.portfolio(er = er, cov.mat = covmat,  
                  target.return = target.return)
```

```
Portfolio expected return:    0.0427  
Portfolio standard deviation: 0.091656  
Portfolio weights:  
  MSFT  NORD  SBUX  
0.8275 -0.0907 0.2633
```

The tangency portfolio \mathbf{t} is the portfolio of risky assets with the highest Sharpe's slope and solves the optimization problem

$$\max_{\mathbf{t}} \frac{\mathbf{t}'\boldsymbol{\mu} - r_f}{(\mathbf{t}'\boldsymbol{\Sigma}\mathbf{t})^{1/2}} \text{ s.t. } \mathbf{t}'\mathbf{1} = 1,$$

where r_f denotes the risk-free rate. To compute this portfolio with $r_f = 0.005$ use the `tangency.portfolio()` function

```
> tan.port <- tangency.portfolio(er, covmat, rk.free)  
> tan.port
```

Call:

```
tangency.portfolio(er = er, cov.mat = covmat, risk.free = rk.free)
```

```
Portfolio expected return:    0.05188967  
Portfolio standard deviation: 0.1115816  
Portfolio weights:  
  MSFT  NORD  SBUX  
1.0268 -0.3263 0.2994
```

The the set of efficient portfolios of risky assets can be computed as a convex combination of any two efficient portfolios. It is convenient to use the global minimum variance portfolio as one portfolio and an efficient portfolio with target expected return equal to the maximum expected return of the assets under consideration as the other portfolio. Call these portfolios \mathbf{m} and \mathbf{x} , respectively. For any number α , another efficient portfolio can be computed as

$$\mathbf{z} = \alpha\mathbf{m} + (1 - \alpha)\mathbf{x}$$

The function `efficient.frontier()` constructs the set of efficient portfolios using this method for a collection of α values. For example, to compute 20 efficient portfolios for values of α between -2 and 1.5 use

```

> ef <- efficient.frontier(er, covmat, alpha.min=-2,
+                          alpha.max=1.5, nport=20)
> attributes(ef)
$names
[1] "call"      "er"        "sd"        "weights"

$class
[1] "Markowitz"

> ef
Call:
efficient.frontier(er = er, cov.mat = covmat, nport = 20, alpha.min = -2,
                  alpha.max = 1.5)

```

Frontier portfolios' expected returns and standard deviations

	port 1	port 2	port 3	port 4	port 5	port 6	port 7
ER	0.0783	0.0750	0.0718	0.0685	0.0652	0.0619	0.0586
SD	0.1826	0.1732	0.1640	0.1548	0.1458	0.1370	0.1284
	port 8	port 9	port 10	port 11	port 12	port 13	port 14
ER	0.0554	0.0521	0.0488	0.0455	0.0422	0.039	0.0357
SD	0.1200	0.1120	0.1044	0.0973	0.0908	0.085	0.0802
	port 15	port 16	port 17	port 18	port 19	port 20	
ER	0.0324	0.0291	0.0258	0.0225	0.0193	0.0160	
SD	0.0764	0.0739	0.0727	0.0730	0.0748	0.0779	

Use the `summary()` method to show the weights of these portfolios. Use the `plot()` method to plot the efficient frontier

```
> plot(ef)
```

The resulting plot is shown in Figure 1.6.

To create a plot of the efficient frontier showing the original assets and the tangency portfolio use

```

> plot(ef, plot.assets=T)
> points(gmin.port$sd, gmin.port$er, col="blue")
> points(tan.port$sd, tan.port$er, col="red")
> sr.tan = (tan.port$er - rk.free)/tan.port$sd
> abline(a=rk.free, b=sr.tan)

```

The resulting plot is shown in Figure 1.7.

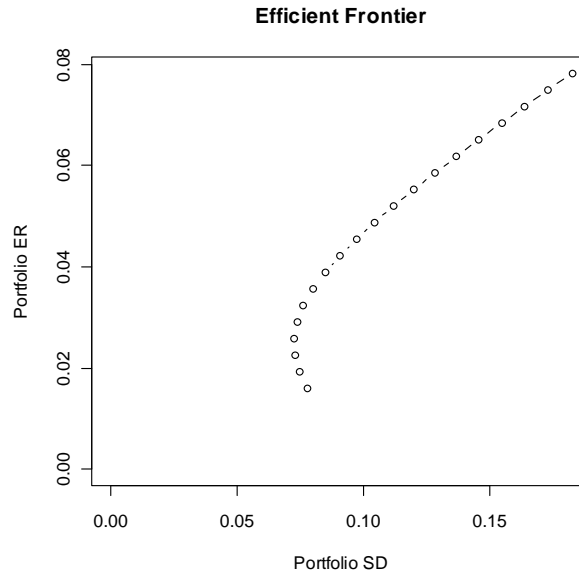


Figure 1.6: Plot method for Markowitz object.

1.3 References

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Ingersoll, Jr., J.E. (1987). *Theory of Financial Decision Making*, Rowman and Littlefield, Totowa, NJ.

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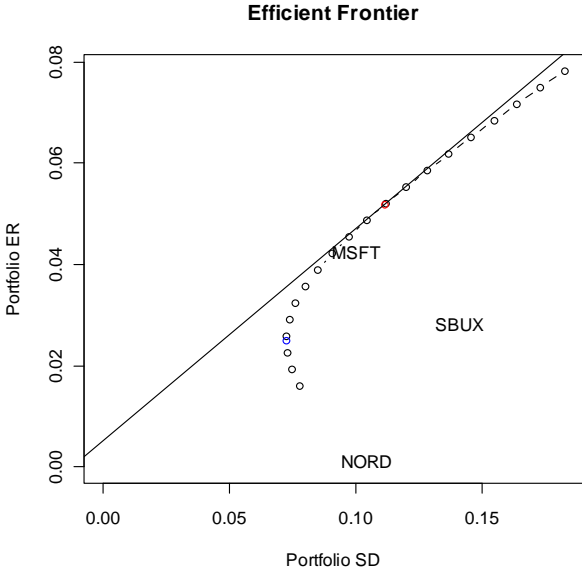


Figure 1.7: Efficient frontier for three firm example.