

Mean-variance portfolio notes

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Contents

Risky Assets	1
Geometry	3
Two Fund Theorem	3
Decomposition	4
Zero covariance	5
Risk-free asset	6
One Fund Theorem	7
Sharpe ratio	9
CAPM	10
Beta representation	10
CAPM	12

Risky Assets

Suppose \mathbf{r} is a $n \times 1$ random vector with mean $\bar{\mathbf{r}}$ and invertible variance \mathbf{V} , then the portfolio return is

$$\mathbf{r}_p = \omega' \mathbf{r}$$

hence $E[\mathbf{r}_p] = \omega' \bar{\mathbf{r}}$ and

$$\text{Cov}(\bar{\mathbf{r}}_p) = \text{cov}(\omega' \mathbf{r}) = \omega' \text{Cov}(\mathbf{r}) \omega = \omega' \mathbf{V} \omega$$

Then the problem is

$$\min \frac{1}{2} \omega' \mathbf{V} \omega \quad s.t. \quad \mathbf{e}' \omega = \mathbf{1}, \omega' \bar{\mathbf{r}} = \bar{r}_p$$

By Lagrangian

$$L = \frac{1}{2}\omega' \mathbf{V} \omega + \lambda(\bar{r}_p - \omega' \bar{\mathbf{r}}) + \gamma(\mathbf{1} - \omega' \mathbf{e})$$

$$\frac{\partial L}{\partial \omega} = \mathbf{V} \omega - \lambda \bar{\mathbf{r}} - \gamma \mathbf{e} = \mathbf{0} \implies \omega^* = \lambda \mathbf{V}^- \bar{\mathbf{r}} + \gamma \mathbf{V}^- \mathbf{e}$$

Hence

$$\begin{aligned} \bar{r}_p &= \bar{\mathbf{r}}' \omega^* = \lambda \bar{\mathbf{r}}' \mathbf{V}^- \bar{\mathbf{r}} + \gamma \bar{\mathbf{r}}' \mathbf{V}^- \mathbf{e} \\ \mathbf{1} &= \mathbf{e}' \omega^* = \lambda \mathbf{e}' \mathbf{V}^- \bar{\mathbf{r}} + \gamma \mathbf{e}' \mathbf{V}^- \mathbf{e} \end{aligned}$$

denoted $\delta = \mathbf{e}' \mathbf{V}^- \mathbf{e}$, $\alpha = \bar{\mathbf{r}}' \mathbf{V}^- \mathbf{e}$, $\xi = \bar{\mathbf{r}}' \mathbf{V}^- \bar{\mathbf{r}}$ where $\delta, \xi > 0$ since \mathbf{V} is positive define. Thus we have a linear equations:

$$\begin{bmatrix} \xi & \alpha \\ \alpha & \delta \end{bmatrix} \begin{bmatrix} \lambda \\ \gamma \end{bmatrix} = \begin{bmatrix} \bar{r}_p \\ 1 \end{bmatrix}$$

Note $\Delta = \delta\xi - \alpha^2 > 0$ since $(\alpha\bar{\mathbf{r}} - \xi\mathbf{e})' \mathbf{V}^- (\alpha\bar{\mathbf{r}} - \xi\mathbf{e}) = \xi(\delta\xi - \alpha^2) > 0$ and thus such equations is consistent.

solve $(\mathbf{A}\mathbf{x} = \mathbf{b} \implies \mathbf{x} = \mathbf{A}^- \mathbf{b})$:

$$\lambda = \frac{\delta\bar{r}_p - \alpha}{\delta\xi - \alpha^2}, \gamma = \frac{\xi - \alpha\bar{r}_p}{\delta\xi - \alpha^2}$$

and

$$\begin{aligned} \omega^* &= \lambda \mathbf{V}^- \bar{\mathbf{r}} + \gamma \mathbf{V}^- \mathbf{e} \\ &= \frac{\delta\bar{r}_p - \alpha}{\delta\xi - \alpha^2} \mathbf{V}^- \bar{\mathbf{r}} + \frac{\xi - \alpha\bar{r}_p}{\delta\xi - \alpha^2} \mathbf{V}^- \mathbf{e} \\ &= a + b\bar{r}_p \end{aligned}$$

where $a = \frac{\xi \mathbf{V}^- \mathbf{e} - \alpha \mathbf{V}^- \bar{\mathbf{r}}}{\delta\xi - \alpha^2}$ and $b = \frac{-\alpha \mathbf{V}^- \mathbf{e} + \delta \mathbf{V}^- \bar{\mathbf{r}}}{\delta\xi - \alpha^2}$

The minimum variance is given by

$$\sigma_p^2 = \omega'^* \mathbf{V} \omega^* = \omega'^* (\lambda \bar{\mathbf{r}} + \gamma \mathbf{e}) = \lambda \bar{r}_p + \gamma$$

by some algebra

$$\lambda \bar{r}_p + \gamma = \frac{1}{\delta} + \frac{\delta(\bar{r}_p - \frac{\alpha}{\delta})^2}{\delta\xi - \alpha^2}$$

Thus the **global minimum variance**(GMV) portfolio is $\frac{1}{\delta}$ when $\bar{r}_p = \frac{\alpha}{\delta}$, meanwhile

$$\begin{aligned}\lambda &= \frac{\delta \bar{r}_p - \alpha}{\delta \xi - \alpha^2} = 0 \\ \gamma &= \frac{\xi - \alpha \bar{r}_p}{\delta \xi - \alpha^2} = \frac{\xi - \alpha \frac{\alpha}{\delta}}{\delta \xi - \alpha^2} = \frac{1}{\delta} \\ \omega_{mv} &= 0 + \frac{\mathbf{V}^{-}\mathbf{e}}{\delta} = \frac{\mathbf{V}^{-}\mathbf{e}}{\mathbf{e}'\mathbf{V}^{-}\mathbf{e}}\end{aligned}$$

Geometry

In geometry view, rewrite $\sigma_p^2 = \frac{1}{\delta} + \frac{\delta(\bar{r}_p - \frac{\alpha}{\delta})^2}{\delta \xi - \alpha^2}$ as

$$\frac{\sigma_p^2}{1/\delta} - \frac{(\bar{r}_p - \frac{\alpha}{\delta})^2}{(\delta \xi - \alpha^2)/\delta^2} = 1$$

it's a hyperbola with center $(0, \alpha/\delta)$ and asymptote $\bar{r}_p = \frac{\alpha}{\delta} \pm \sqrt{\frac{\delta \xi - \alpha^2}{\delta}} \sigma_p$ (recall that asymptote is $y = \pm \frac{b}{a}x$ in $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$).

Two Fund Theorem

The mean-variance frontier can be replicated by any two frontier portfolios and any linear combination of frontier portfolios is on the frontier.

Suppose r_1 and r_2 are any given expected return, note

$$\forall r_3, \exists x \ni x r_1 + (1 - x) r_2 = r_3$$

Then the weight combined such way is just what we want.

$$\omega_3 = x \omega_1 + (1 - x) \omega_2 = x(a + b r_1) + (1 - x)(a + b r_2) = a + b r_3$$

Any convex combination of efficient frontier portfolios will be an efficient frontier portfolio.

Proof A portfolio ω is on the efficient frontier iff (if and only if) its return $\bar{r}_p \geq r_{mv}$ and recall $\omega = a + b \bar{r}_p$, thus there is a bijection between ω_i and r_i . Suppose the return of ω_i is r_i ,

$$\omega = [\omega_1 \quad \cdots \quad \omega_n], \mathbf{c} = \begin{bmatrix} c_1 \\ \vdots \\ c_n \end{bmatrix}$$

Firstly, verify the convex combination is a legal portfolio:

$$\mathbf{e}'(\omega\mathbf{c}) = (\mathbf{e}'\omega)\mathbf{c} = \mathbf{e}'\mathbf{c} = 1$$

since $\forall \omega_i \mathbf{e}'\omega_i = 1, \mathbf{e}'\mathbf{c} = 1$. Then it's sufficient to show that $\mathbf{c}'\mathbf{r} \geq r_{mv}$. It's clearly since

$$\mathbf{c}'\mathbf{r} = \sum c_i \omega_i \geq \sum c_i \min(r_i) = \min(r_i) \sum c_i = \min(r_i) \geq r_{mv}$$

Decomposition

Suppose covariance between portfolios p and q

$$\text{Cov}(\mathbf{r}_p, \mathbf{r}_q) = \omega_p' \mathbf{V} \omega_q$$

Suppose q on the frontier, then

$$\omega_p' \mathbf{V} \omega_q = \omega_p' (\lambda \bar{\mathbf{r}} + \gamma \mathbf{e})$$

Moreover, if

1. p is GMV portfolio, then

$$\omega_p' (\lambda \bar{\mathbf{r}} + \gamma \mathbf{e}) = \omega_p' \left(\frac{1}{\delta} \mathbf{e} \right) = \frac{1}{\delta}$$

2. p has the same expected return with q , then

$$\omega_p' (\lambda \bar{\mathbf{r}} + \gamma \mathbf{e}) = \lambda \bar{r}_q + \gamma = \sigma_q^2$$

Thus we have

The covariance of the return on the global minimum variance (GMV) portfolio and that on any portfolio (not necessary on the frontier) is always equal to $\sigma_{mv}^2 = \frac{1}{\delta}$.

Apply this we get $\text{Cov}(\mathbf{r}_p - \mathbf{r}_{mv}, \mathbf{r}_{mv}) = \text{Cov}(\mathbf{r}_p, \mathbf{r}_{mv}) - \sigma_{mv}^2 = 0$ immediately. We call $\epsilon = \mathbf{r}_p - \mathbf{r}_{mv}$ **excess return**.

The covariance of the return on a frontier portfolio q and that on any portfolio p (not on the frontier) with the same expected return as q is always equal to the variance of the frontier portfolio q . Formally $E[\mathbf{r}_p] = E[\mathbf{r}_q] \implies \text{Cov}(\mathbf{r}_p, \mathbf{r}_q) = \sigma_q^2$.

It implies that we can decompose $\mathbf{r}_p = \mathbf{r}_q + \epsilon_p$ where $E[\epsilon] = \text{Cov}(\epsilon_p, \mathbf{r}_q) = 0$

Rewrite the excess return as $\epsilon = b_p \mathbf{r}^*$, then \mathbf{r}_p can be decomposed into

$$\mathbf{r}_p = \mathbf{r}_{mv} + b_p \mathbf{r}^* + \epsilon_p$$

where \mathbf{r}^* is an excess return and $b_p \in \mathbb{R}$. Note $\text{Cov}(\mathbf{r}_{mv}, \epsilon_p) = \text{Cov}(\mathbf{r}_{mv}, \mathbf{r}_p - \mathbf{r}_q) = 0$ then $\text{Cov}(\mathbf{r}^*, \epsilon_p)$ is also zero. Hence

$$\text{Var}(\mathbf{r}_p) = \underbrace{\underbrace{\sigma_{mv}^2}_{\text{unavoidable risk}} + \underbrace{b_p^2 \text{Var}(\mathbf{r}^*)}_{\text{systematic risk}}}_{\text{unavoidable risk}} + \underbrace{\text{Var}(\epsilon_p)}_{\text{idiot risk}}$$

One can reduce ϵ_p to zero to avoid idiot risk and get a frontier portfolio.

Zero covariance

Continue the discussion of the covariance between p and q , now suppose they are both on frontier:

$$\omega_p' \mathbf{V} \omega_q = \frac{1}{\delta} + \frac{\delta(\bar{r}_p - \frac{\alpha}{\delta})(\bar{r}_q - \frac{\alpha}{\delta})}{\delta\xi - \alpha^2}$$

Setting this to 0 and solve for \bar{r}_q

$$\bar{r}_q = \frac{\alpha}{\delta} - \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)}$$

Then we are ready to show that

\bar{r}_q is equal to the intercept of the tangent line to MVF at (\bar{r}_p, σ_p)

Suppose the tangent line in \bar{r}_p , the slope is

$$\frac{\partial \bar{r}_p}{\partial \sigma_p} = \frac{\delta\xi - \alpha^2}{\delta(\bar{r}_p - \frac{\alpha}{\delta})} \sigma_p$$

(Recall $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1 \implies \frac{2x}{a^2} - \frac{2yy'}{b^2} = 0 \implies y' = \frac{b^2 x^2}{a^2 y^2}$)

thus its intercept at $\sigma_p = 0$ is

$$\bar{r}_p - \frac{\delta\xi - \alpha^2}{\delta(\bar{r}_p - \frac{\alpha}{\delta})} \sigma_p^2 = \bar{r}_p - \frac{\delta\xi - \alpha^2}{\delta(\bar{r}_p - \frac{\alpha}{\delta})} \left(\frac{1}{\delta} + \frac{\delta(\bar{r}_p - \frac{\alpha}{\delta})^2}{\delta\xi - \alpha^2} \right) = \frac{\alpha}{\delta} - \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)} = \bar{r}_q$$

Let $\bar{r}_q = 0$, then

$$\frac{\alpha}{\delta} - \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)} = 0$$

solve for \bar{r}_p , we get

$$\bar{r}_p = \frac{\delta\xi - \alpha^2}{\alpha\delta} + \frac{\alpha}{\delta}$$

Substituted in $a + b\bar{r}_p$:

$$\omega_D = -\frac{\mathbf{V}^-\mathbf{e}}{\delta} + \frac{\mathbf{V}^-\bar{\mathbf{r}}}{\alpha} + (a+b)\frac{\alpha}{\delta} = -\frac{\mathbf{V}^-\mathbf{e}}{\delta} + \frac{\mathbf{V}^-\bar{\mathbf{r}}}{\alpha} + \frac{\mathbf{V}^-\mathbf{e}}{\delta} = \frac{\mathbf{V}^-\bar{\mathbf{r}}}{\alpha}$$

That is the tangency portofolio. If $\bar{r}_q > 0$, \bar{r}_q can be interpreted as risk-free asset return in next chapter

Risk-free asset

Suppose we have a riskless asset with return r_f , and we assign ω_0 weight on it. Then the portfolio choice problem becomes

$$\min_{\omega, \omega_0} \frac{1}{2} \omega' \mathbf{V} \omega \quad s.t. \quad \mathbf{e}' \omega + \omega_0 = 1, \omega' \bar{\mathbf{r}} + \omega_0 r_f = \bar{r}_p$$

substitute $\omega_0 = 1 - \mathbf{e}' \omega$, then

$$\omega' \bar{\mathbf{r}} + (1 - \mathbf{e}' \omega) r_f = \bar{r}_p \implies \omega' (\bar{\mathbf{r}} - r_f \mathbf{e}) + r_f = \bar{r}_p$$

The problem is

$$\min_{\omega, \omega_0} \frac{1}{2} \omega' \mathbf{V} \omega \quad s.t. \quad \omega' (\bar{\mathbf{r}} - r_f \mathbf{e}) + r_f = \bar{r}_p$$

Again by the Lagrangian:

$$L = \frac{1}{2} \omega' \mathbf{V} \omega + \lambda (\bar{r}_p - \omega' (\bar{\mathbf{r}} - r_f \mathbf{e}) - r_f)$$

$$\frac{\partial L}{\partial \omega} = \mathbf{V} \omega - \lambda (\bar{\mathbf{r}} - r_f \mathbf{e}) = 0 \implies \omega^* = \lambda \mathbf{V}^{-1} (\bar{\mathbf{r}} - r_f \mathbf{e})$$

$$\bar{r}_p - \omega^{*'}(\bar{\mathbf{r}} - r_f \mathbf{e}) - r_f = 0 \implies \lambda = \frac{\bar{r}_p - r_f}{(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})}$$

$$\sigma_p^2 = \omega' \mathbf{V} \omega = \lambda^2 (\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^{-} \mathbf{V} \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e}) = \frac{(\bar{r}_p - r_f)^2}{(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})}$$

In geometry view, the frontier degenerate into two crossing line:

$$\bar{r}_p = r_f \pm \sqrt{(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})} \sigma_p$$

One Fund Theorem

Substitutue λ in the expression of ω^* :

$$\omega^* = \frac{(\bar{r}_p - r_f)}{(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})} \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})$$

We denote $c = \frac{(\bar{r}_p - r_f)}{(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})}$ (since it's a scalar) and $\tilde{\omega} = \mathbf{V}^{-} (\bar{\mathbf{r}} - r_f \mathbf{e})$ then we can write

$$\omega^* = c \tilde{\omega}$$

That is so called one fund theorem

When $r_f \neq r_{mv}$ any minimal-variance frontier portfolio is a combination of the tangency portfolio (with risk assets only) and the riskless asset

Normalized $\tilde{\omega}(\frac{\tilde{\omega}}{\mathbf{e}'\tilde{\omega}})$ is the tangency portfolio, i.e. $\omega_D = \frac{\tilde{\omega}}{\mathbf{e}'\tilde{\omega}}$, the reason is showing below.

Now we prove the degenerated frontier is tangent to the the origin frontier, that is, the hyperbola $\frac{\sigma_p^2}{1/\delta} - \frac{(\bar{r}_p - \frac{\alpha}{\delta})^2}{(\delta\xi - \alpha^2)/\delta^2} = 1$. Assume they do tangent and the tangent point is (σ_p, \bar{r}_p)

Recall the polar of (x_0, y_0) w.r.t. $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$ is $\frac{x_0 x}{a^2} - \frac{y_0 y}{b^2} = 1$ and the slope is

$$\frac{b^2 x_0}{a^2 y_0} = \sqrt{\frac{b^4 x_0^2}{a^4 y_0^2}} = \sqrt{\frac{b^2(a^2 b^2 + a^2 y_0^2)}{a^4 y_0^2}}$$

Then since the tangent line through $(0, r_f)$:

$$-\frac{(\bar{r}_p - \frac{\alpha}{\delta})(r_f - \frac{\alpha}{\delta})}{\Delta/\delta^2} = 1$$

solved for \bar{r}_p :

$$\bar{r}_p = \frac{-\alpha^2 + r_f \alpha \delta - \Delta}{\delta(-\alpha + r_f \delta)} = \frac{\xi - r_f \alpha}{\alpha - r_f \delta}$$

the square of slope is

$$\begin{aligned} \frac{\Delta \left(\frac{\Delta}{\delta^3} + \frac{(y_0 - \frac{\alpha}{\delta})^2}{\delta} \right)}{(y_0 - \frac{\alpha}{\delta})^2} &= \frac{\Delta (\alpha^2 + \Delta + \delta^2 y_0^2 - 2\alpha \delta y_0)}{\delta(\alpha - \delta y_0^2)} \\ &= \frac{\Delta \left(\alpha^2 + \Delta - \frac{2\alpha(-\alpha^2 - \Delta + \alpha \delta r_f)}{\delta r_f - \alpha} + \frac{(-\alpha^2 - \Delta + \alpha \delta r_f)^2}{(\delta r_f - \alpha)^2} \right)}{\delta \left(\alpha - \frac{-\alpha^2 - \Delta + \alpha \delta r_f}{\delta r_f - \alpha} \right)^2} \\ &= \frac{\alpha^2 + \Delta + \delta^2 r_f^2 - 2\alpha \delta r_f}{\delta} \\ &= \xi + \delta r_f^2 - 2\alpha r_f \end{aligned}$$

Which is equal to

$$(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e}) = \xi + \delta r_f^2 - 2\alpha r_f$$

Hence our assumption is correct. Consider the tangency portfolio:

$$\bar{r}_p = \frac{\xi - r_f \alpha}{\alpha - r_f \delta} = \frac{\Delta / \delta^2}{r_{mv} - r_f} + r_{mv}$$

If $r_f = \frac{\alpha}{\delta} = r_{mv}$, the tangency doesn't exist and the frontier becomes asymptotes.
If $r_f > r_{mv}$, the tangency is in the lower straight line and vice versa.

The weight is

$$\omega^* = a + b \bar{r}_p = \frac{\mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e})}{\alpha - \delta r_f} = \frac{\mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e})}{\mathbf{e}' \mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e})} = \frac{\tilde{\omega}}{\mathbf{e}' \tilde{\omega}}$$

That is why we called $\tilde{\omega}$ tangency portfolio. Recall the result in zero covariance, for any portfolio $\bar{r}_p > r_{mv}$, we can find $r_f = \bar{r}_q$ with zero covariance with \bar{r}_p to make \bar{r}_p be a tangency portfolio.

Sharpe ratio

The sharpe ratio is defined by

$$S_p = \frac{\bar{r}_p - r_f}{\sigma_p} = \frac{\omega'(\bar{\mathbf{r}} - r_f \mathbf{e})}{\sqrt{\omega' \mathbf{V} \omega}}$$

Which can be interpreted as a measure of **expected excess return per unit of risk**.

To maximize S_p , suppose

$$\frac{\partial S_p}{\partial \omega} = 0$$

Let $\mathbf{r} = \bar{\mathbf{r}} - r_f \mathbf{e}$

$$\phi : w \mapsto \begin{bmatrix} \omega' \mathbf{r} \\ \omega' \mathbf{V} \omega \end{bmatrix}, \quad h(x, y) := \frac{x}{y^{1/2}}$$

Then $S_p = h \circ \phi(w)$, and thus

$$\begin{aligned} \frac{\partial S_p}{\partial \omega} &= \frac{\partial h}{\partial \phi} \frac{\partial \phi}{\partial \omega} \\ &= \begin{bmatrix} \frac{1}{(\omega' \mathbf{V} \omega)^{1/2}} & -\frac{\omega' \mathbf{r}}{2(\omega' \mathbf{V} \omega)^{3/2}} \end{bmatrix} \begin{bmatrix} \mathbf{r}' \\ 2\omega' \mathbf{V} \end{bmatrix} \\ &= \frac{\omega' \mathbf{V} \omega \mathbf{r}' - \omega' \mathbf{r} \omega' \mathbf{V}}{(\omega' \mathbf{V} \omega)^{3/2}} \end{aligned}$$

Setting to zero,

$$\omega' \mathbf{V} \omega \mathbf{r}' - \omega' \mathbf{r} \omega' \mathbf{V} = \mathbf{0} \implies \omega = \frac{\omega' \mathbf{V} \omega}{\omega' \mathbf{r}} \mathbf{V}^- \mathbf{r}$$

Note the scale of ω is independent to S_p . If we assume $\mathbf{e}' \omega = 1$ additionally, then

$$\omega = \frac{\mathbf{V}^- \mathbf{r}}{\mathbf{e}' \mathbf{V}^- \mathbf{r}} = \frac{\mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e})}{\mathbf{e}' \mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e})} = \frac{\tilde{\omega}}{\mathbf{e}' \tilde{\omega}} = \omega_D$$

Remark

1. The maximum sharpe ratio is the slope of frontier $\sqrt{(\bar{\mathbf{r}} - r_f \mathbf{e})' \mathbf{V}^- (\bar{\mathbf{r}} - r_f \mathbf{e})}$.
2. ω_D is the only maxima on the frontier without risk-free asset. However, every portfolio on the frontier with a risk-free asset has the maximal sharpe ratio by one fund theorem ($\omega^* = c\tilde{\omega}$) if $r_f > r_{mv}$. (Otherwise ω_D is on the lower straight line and become a minima).

CAPM

Beta representation

Recall the tangency portfolio is $\omega_D = \frac{\mathbf{V}^-(\bar{\mathbf{r}} - r_f \mathbf{e})}{\mathbf{e}' \mathbf{V}^-(\bar{\mathbf{r}} - r_f \mathbf{e})}$. Write $\omega_D = m \mathbf{V}^-(\bar{\mathbf{r}} - r_f \mathbf{e})$ where $m = \frac{1}{\mathbf{e}' \mathbf{V}^-(\bar{\mathbf{r}} - r_f \mathbf{e})}$, then we have

$$\bar{\mathbf{r}} - r_f \mathbf{e} = \frac{1}{m} \mathbf{V} \omega_D$$

Note $\text{Cov}(\mathbf{r}, \omega'_D \mathbf{r}) = \mathbf{V} \omega_D$ and

$$\sigma_D^2 = \omega'_D \mathbf{V} \omega_D = m \omega'_D (\bar{\mathbf{r}} - r_f \mathbf{e}) = m r_D - m r_f$$

we have

$$\bar{\mathbf{r}} - r_f \mathbf{e} = \frac{r_D - r_f}{\sigma_D^2} \text{Cov}(\mathbf{r}, r_D)$$

Denote $\frac{\text{Cov}(\mathbf{r}, r_D)}{\sigma_D^2} = \beta_D$, we have

$$\bar{\mathbf{r}} - r_f \mathbf{e} = \beta_D (r_D - r_f)$$

Similar results also holds for any portfolio \bar{r}_p in the MVF:

$$\bar{\mathbf{r}} - \bar{r}_q \mathbf{e} = \beta_p (\bar{r}_p - \bar{r}_q)$$

It's clear in the view of every portfolio \bar{r}_p is also a tangency portfolio by selecting proper r_f . One can also check it in a dirty way:

Proof Suppose r_p and r_q both in the MVF without risk-free asset, recall

$$\omega'_p \mathbf{V} \omega_q = \frac{1}{\delta} + \frac{\delta(\bar{r}_p - \frac{\alpha}{\delta})(\bar{r}_q - \frac{\alpha}{\delta})}{\delta\xi - \alpha^2}$$

If the covariance is 0, we have

$$\bar{r}_q = \frac{\alpha}{\delta} - \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)}$$

Then

$$\begin{aligned}
\bar{\mathbf{r}} - \bar{r}_q \mathbf{e} &= \bar{\mathbf{r}} - \left(\frac{\alpha}{\delta} - \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)} \right) \mathbf{e} \\
&= \frac{1}{\delta^2(\bar{r}_p - \alpha/\delta)} (\delta^2(\bar{r}_p - \alpha/\delta)) (\bar{\mathbf{r}} - \left(\frac{\alpha}{\delta} - \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)} \right) \mathbf{e}) \\
&= \frac{1}{\delta^2(\bar{r}_p - \alpha/\delta)} (\bar{\mathbf{r}}(\delta^2(\bar{r}_p - \alpha/\delta)) - (\alpha\delta(\bar{r}_p - \alpha/\delta) - (\delta\xi - \alpha^2)) \mathbf{e}) \\
&= \frac{1}{\delta^2(\bar{r}_p - \alpha/\delta)} (\bar{\mathbf{r}}(\delta^2(\bar{r}_p - \alpha/\delta)) - (\alpha\delta\bar{r}_p - \delta\xi) \mathbf{e}) \\
&= \frac{(\delta^2\bar{r}_p\bar{\mathbf{r}} - \alpha\delta\bar{\mathbf{r}}) - (\alpha\delta\bar{r}_p - \delta\xi) \mathbf{e}}{\delta^2(\bar{r}_p - \alpha/\delta)} \\
&= \frac{(\delta\bar{r}_p - \alpha)\bar{\mathbf{r}} - (\alpha\bar{r}_p - \xi) \mathbf{e}}{\delta(\bar{r}_p - \alpha/\delta)}
\end{aligned}$$

On the other hand:

$$\begin{aligned}
\beta_p &= \frac{\mathbf{V}\omega_{\mathbf{p}}}{\omega'_p \mathbf{V}\omega_p} \\
&= \frac{1}{\omega'_p \mathbf{V}\omega_p} (\lambda_p \bar{\mathbf{r}} + \gamma \mathbf{e}) \\
&= \frac{1}{\omega'_p \mathbf{V}\omega_p} \left(\frac{\xi \mathbf{e} - \alpha \bar{\mathbf{r}}}{\delta\xi - \alpha^2} + \frac{-\alpha \mathbf{e} + \delta \bar{\mathbf{r}}}{\delta\xi - \alpha^2} \bar{r}_p \right) \\
&= \frac{1}{\omega'_p \mathbf{V}\omega_p} \left(\frac{(\delta\bar{r}_p - \alpha)\bar{\mathbf{r}} - (\alpha\bar{r}_p - \xi) \mathbf{e}}{\Delta} \right)
\end{aligned}$$

Then it's remain to show that

$$(\bar{r}_p - \bar{r}_q)\delta(\bar{r}_p - \alpha/\delta) = \omega' \mathbf{V}\omega \Delta$$

It's clear since

$$\omega' \mathbf{V}\omega \Delta = \sigma_p^2 \Delta = \frac{\Delta}{\delta} + \delta(\bar{r}_p - \frac{\alpha}{\delta})^2$$

and

$$\begin{aligned}
(\bar{r}_p - \bar{r}_q)\delta(\bar{r}_p - \alpha/\delta) &= \left((\bar{r}_p - \frac{\alpha}{\delta}) + \frac{\delta\xi - \alpha^2}{\delta^2(\bar{r}_p - \alpha/\delta)} \right) \delta(\bar{r}_p - \alpha/\delta) \\
&= \frac{\Delta}{\delta} + \delta(\bar{r}_p - \frac{\alpha}{\delta})^2. \blacksquare
\end{aligned}$$

CAPM

In capital market equilibrium, the market portfolio is tangency portfolio $r_D = r_m$, then

$$\bar{\mathbf{r}} - r_f \mathbf{e} = \beta_m (r_m - r_f)$$

where

$$\beta_m = \begin{bmatrix} \frac{\text{Cov}(r_1, r_m)}{\sigma_m^2} \\ \frac{\text{Cov}(r_2, r_m)}{\sigma_m^2} \\ \dots \\ \frac{\text{Cov}(r_n, r_m)}{\sigma_m^2} \end{bmatrix}$$

this equation is called **Sharpe-Lintner CAPM**. $r_m - r_f$ is called **market risk premium** and $\frac{r_m - r_f}{\sigma_m}$ is called **market sharpe ration**. Translate it from vector form, we get the **Security Market Line**:

$$r_i - r_f = \frac{\text{Cov}(r_i, r_m)}{\sigma_m^2} (r_m - r_f) = \beta_{i,m} (r_m - r_f)$$

Now consider both r_i and r_m is random variable, let ϵ be a random vector with zero expectation and zero covariance with r_i and r_m , then

$$\mathbf{r} - r_f \mathbf{e} = (r_m - r_f) \beta_m + \epsilon$$

thus

$$\begin{aligned} \text{Var}(\mathbf{r}) &= \text{Var}(\mathbf{r} - r_f \mathbf{e}) \\ &= \text{Var}(\beta_m (r_m - r_f)) + \text{Var}(\epsilon) \\ &= \text{Var}(r_m \beta_m) + \text{Var}(\epsilon) \\ &= \beta_m \beta_m' \sigma_m^2 + \text{Var}(\epsilon) \end{aligned}$$