Investors may wish to adjust the allocation of financial resources including a mixture of cash, bonds, stocks, options, and other financial instruments is such as manner to achieve some time of optimality.

There are various, equally valid notions of optimality.

- Maximum rate of return on a portfolio.
- Minimum deviation from a chosen rate of return.
- Minimum risk of loss of portfolio value.
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There are various, equally valid notions of optimality.

- Maximum rate of return on a portfolio.
- Minimum deviation from a chosen rate of return.
- Minimum risk of loss of portfolio value.

The investor must choose the type of optimality they wish their portfolio to have.
**Definition**

**Covariance** is a measure of the degree to which two random variables tend to change in the same or opposite direction relative to one another. If $X$ and $Y$ are the random variables then the covariance, denoted $\text{Cov}(X, Y)$, is defined as

$$\text{Cov}(X, Y) = \mathbb{E}[(X - \mathbb{E}[X])(Y - \mathbb{E}[Y])].$$
Theorem

If $X$ and $Y$ are random variables then

$$\text{Cov}(X, Y) = \mathbb{E}[XY] - \mathbb{E}[X] \mathbb{E}[Y].$$
Theorem

If $X$ and $Y$ are random variables then

$$\text{Cov}(X, Y) = E[XY] - E[X]E[Y].$$

$$\begin{align*}
                 &= E[XY] - E[X]E[Y]
\end{align*}$$
Consider the following table listing the heights and arm spans of 20 children (source).

<table>
<thead>
<tr>
<th>Child</th>
<th>Ht. (cm)</th>
<th>Span (cm)</th>
<th>Child</th>
<th>Ht. (cm)</th>
<th>Span (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>142</td>
<td>138</td>
<td>11</td>
<td>150</td>
<td>147</td>
</tr>
<tr>
<td>2</td>
<td>148</td>
<td>144</td>
<td>12</td>
<td>152</td>
<td>141</td>
</tr>
<tr>
<td>3</td>
<td>152</td>
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<td>13</td>
<td>148</td>
<td>144</td>
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<td>4</td>
<td>150</td>
<td>145</td>
<td>14</td>
<td>152</td>
<td>148</td>
</tr>
<tr>
<td>5</td>
<td>141</td>
<td>136</td>
<td>15</td>
<td>144</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>142</td>
<td>139</td>
<td>16</td>
<td>148</td>
<td>143</td>
</tr>
<tr>
<td>7</td>
<td>149</td>
<td>144</td>
<td>17</td>
<td>150</td>
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<tr>
<td>8</td>
<td>151</td>
<td>145</td>
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<td>138</td>
<td>134</td>
</tr>
<tr>
<td>9</td>
<td>147</td>
<td>144</td>
<td>19</td>
<td>145</td>
<td>142</td>
</tr>
<tr>
<td>10</td>
<td>152</td>
<td>148</td>
<td>20</td>
<td>142</td>
<td>138</td>
</tr>
</tbody>
</table>

Find the covariance of height and arm span.
If $X$ represents height and $Y$ represents arm span then

$$\begin{align*}
E[X] &= 147.15 \\
E[Y] &= 142.70 \\
E[XY] &= 21013.8
\end{align*}$$

which implies

$$\text{Cov}(X, Y) = 21013.8 - (147.15)(142.70) = 15.445.$$  

**Note:** since $\text{Cov}(X, Y) > 0$, then in general as height increases so does arm span.
Theorem

If $X$ and $Y$ are independent random variables then
$\text{Cov} (X, Y) = 0$. 
Theorem

If $X$ and $Y$ are independent random variables then
$\text{Cov}(X, Y) = 0$.

Proof.

Theorem

Suppose $X$, $Y$, and $Z$ are random variables, then the following statements are true:

1. $\text{Cov}(X, X) = \text{Var}(X),$
2. $\text{Cov}(X, Y) = \text{Cov}(Y, X),$
3. $\text{Cov}(X + Y, Z) = \text{Cov}(X, Z) + \text{Cov}(Y, Z).$
Proof

Let $X$, $Y$, and $Z$ be random variables, then

$$\text{Cov}(X + Y, Z) = \mathbb{E}[(X + Y)Z] - \mathbb{E}[X + Y] \mathbb{E}[Z]$$

$$= \mathbb{E}[XZ] + \mathbb{E}[YZ] - \mathbb{E}[X] \mathbb{E}[Z] - \mathbb{E}[Y] \mathbb{E}[Z]$$

$$= \mathbb{E}[XZ] - \mathbb{E}[X] \mathbb{E}[Z] + \mathbb{E}[YZ] - \mathbb{E}[Y] \mathbb{E}[Z]$$

$$= \text{Cov}(X, Z) + \text{Cov}(Y, Z)$$
Corollary

Suppose \( \{X_1, X_2, \ldots, X_n\} \) and \( \{Y_1, Y_2, \ldots, Y_m\} \) are sets of random variables where \( n, m \geq 1 \).

\[
\text{Cov} \left( \sum_{i=1}^{n} X_i, \sum_{i=1}^{m} Y_i \right) = \sum_{i=1}^{n} \sum_{j=1}^{m} \text{Cov} \left( X_i, Y_j \right)
\]
Let \( \{X_1, X_2, \ldots, X_k, X_{k+1}\} \) be random variables.

\[
\text{Cov} \left( \sum_{i=1}^{k+1} X_i, Y_1 \right) = \text{Cov} \left( \sum_{i=1}^{k} X_i, Y_1 \right) + \text{Cov} \left( X_{k+1}, Y_1 \right) \\
= \sum_{i=1}^{k} \text{Cov} \left( X_i, Y_1 \right) + \text{Cov} \left( X_{k+1}, Y_1 \right) \\
= \sum_{i=1}^{k+1} \text{Cov} \left( X_i, Y_1 \right)
\]

Therefore by induction we may show that the result is true for any finite, integer value of \( n \) and \( m = 1 \).
When $m > 1$ we can argue that

$$\text{Cov} \left( \sum_{i=1}^{n} X_i, \sum_{j=1}^{m} Y_j \right) = \sum_{i=1}^{n} \text{Cov} \left( X_i, \sum_{j=1}^{m} Y_j \right)$$

$$= \sum_{i=1}^{n} \text{Cov} \left( \sum_{j=1}^{m} Y_j, X_i \right)$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{m} \text{Cov} \left( Y_j, X_i \right)$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{m} \text{Cov} \left( X_i, Y_j \right) .$$
Corollary

If \( \{X_1, X_2, \ldots, X_n\} \) are random variables then

\[
\text{Var} \left( \sum_{i=1}^{n} X_i \right) = \sum_{i=1}^{n} \text{Var} (X_i) + \sum_{i=1}^{n} \sum_{j \neq i} \text{Cov} (X_i, X_j).
\]
Proof

Let \( Y = \sum_{i=1}^{n} X_i \), then

\[
\begin{align*}
\text{Var}(Y) &= \text{Cov}(Y, Y) \\
\text{Var}\left(\sum_{i=1}^{n} X_i\right) &= \text{Cov}\left(\sum_{i=1}^{n} X_i, \sum_{j=1}^{n} X_j\right) \\
&= \sum_{i=1}^{n} \sum_{j=1}^{n} \text{Cov}(X_i, X_j) \\
&= \sum_{i=1}^{n} \text{Cov}(X_i, X_i) + \sum_{i=1}^{n} \sum_{j \neq i}^{n} \text{Cov}(X_i, X_j) \\
&= \sum_{i=1}^{n} \text{Var}(X_i) + \sum_{i=1}^{n} \sum_{j \neq i}^{n} \text{Cov}(X_i, X_j)
\end{align*}
\]
Correlation

More informative than covariance would be information that large changes in random variable $X$ are accompanied by large changes in $Y$.

**Definition**

If $X$ and $Y$ are random variables then the **correlation** of $X$ and $Y$ denoted $\rho(X, Y)$ and defined as

$$\rho(X, Y) = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X) \text{ Var}(Y)}}.$$
More informative than covariance would be information that large changes in random variable $X$ are accompanied by large changes in $Y$.

**Definition**

If $X$ and $Y$ are random variables then the **correlation** of $X$ and $Y$ denoted $\rho (X, Y)$ and defined as

$$\rho (X, Y) = \frac{\text{Cov} (X, Y)}{\sqrt{\text{Var} (X) \text{Var} (Y)}}.$$

**Theorem**

If $X$ and $Y$ are independent random variables then $\rho (X, Y) = 0$. We say that $X$ and $Y$ are **uncorrelated**.
Properties of the Correlation

Theorem

Suppose $X$ and $Y$ are random variables such that $Y = aX + b$ where $a, b \in \mathbb{R}$ with $a \neq 0$. If $a > 0$ then $\rho(X, Y) = 1$, while if $a < 0$ then $\rho(X, Y) = -1$. 
Proof

\[
\operatorname{Cov}(X, Y) = \operatorname{Cov}(X, aX + b)
\]
\[
= E[X(aX + b)] - E[X]E[aX + b]
\]
\[
= E\left[ aX^2 + bX \right] - E[X] (aE[X] + b)
\]
\[
= aE\left[ X^2 \right] + bE[X] - aE[X]E[X] - bE[X]
\]
\[
= a \left( E\left[ X^2 \right] - E[X]^2 \right)
\]
\[
= a \operatorname{Var}(X)
\]

\[
\rho(X, Y) = \frac{a \operatorname{Var}(X)}{\sqrt{\operatorname{Var}(X) \cdot a^2 \operatorname{Var}(X)}} = \frac{a}{|a|}
\]
We would like to prove that the correlation of two random variables is always in the interval \([-1, 1]\). First, we need the following inequality.

**Lemma (Schwarz Inequality)**

*If \(X\) and \(Y\) are random variables then*

\[
(E[XY])^2 \leq E[X^2] E[Y^2].
\]
If $a$ and $b$ are real numbers then the following two inequalities hold:

$$0 \leq E[(aX + bY)^2] = a^2 E[X^2] + 2abE[XY] + b^2 E[Y^2]$$

If we let $a^2 = E[Y^2]$ and $b^2 = E[X^2]$ then the inequality above yields

$$0 \leq 2E[X^2]E[Y^2] + 2\sqrt{E[Y^2]E[X^2]E[XY]}$$


$$-\sqrt{E[X^2]E[Y^2]} \leq E[XY].$$
\[ 0 \leq E[(aX - bY)^2] = a^2E[X^2] - 2abE[XY] + b^2E[Y^2] \]

If we let \( a^2 = E[Y^2] \) and \( b^2 = E[X^2] \) then

\[ E[XY] \leq \sqrt{E[X^2] E[Y^2]} . \]

Therefore, since

\[ -\sqrt{E[X^2] E[Y^2]} \leq E[XY] \leq \sqrt{E[X^2] E[Y^2]} \]

\[ (E[XY])^2 \leq E[X^2] E[Y^2] . \]
Theorem

If $X$ and $Y$ are random variables then $-1 \leq \rho(X, Y) \leq 1$. 

Proof.

\[
\text{Cov}(X, Y) \leq \sqrt{\text{Var}(X) \cdot \text{Var}(Y)},
\]

which is equivalent to

\[-1 \leq \rho(X, Y) \leq 1.\]
Range of the Correlation

**Theorem**

*If* $X$ *and* $Y$ *are random variables then* $-1 \leq \rho(X, Y) \leq 1$.

**Proof.**

$$(\text{Cov}(X, Y))^2 = \left( \mathbb{E} \left[ (X - \mathbb{E}[X])(Y - \mathbb{E}[Y]) \right] \right)^2$$

$$\leq \mathbb{E} \left[ (X - \mathbb{E}[X])^2 \right] \mathbb{E} \left[ (Y - \mathbb{E}[Y])^2 \right]$$

$$= \text{Var}(X) \text{Var}(Y)$$

Thus $|\text{Cov}(X, Y)| \leq \sqrt{\text{Var}(X) \text{Var}(Y)}$, which is equivalent to

$$-1 \leq \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X) \text{Var}(Y)}} \leq 1$$

$$-1 \leq \rho(X, Y) \leq 1.$$
For the height and armspan data of the previous example, calculate the correlation between height and armspan.

\[
\rho(X, Y) = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X) \cdot \text{Var}(Y)}} = 15.445 \sqrt{18.6605 \cdot 16.8526} \approx 0.870948
\]
For the height and armspan data of the previous example, calculate the correlation between height and armspan.

\[ \rho(X, Y) = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X) \text{Var}(Y)}} = \frac{15.445}{\sqrt{(18.6605)(16.8526)}} \approx 0.870948. \]
Suppose a portfolio consists of investments \( \{w_1, w_2, \ldots, w_n\} \) with corresponding random variable rates of return \( \{R_1, R_2, \ldots, R_n\} \).

If the total accumulated value of the portfolio after one time period is 
\[
W = \sum_{i=1}^{n} w_i (1 + R_i)
\]
then
\[
E[W] = E \left[ \sum_{i=1}^{n} w_i (1 + R_i) \right] = \sum_{i=1}^{n} w_i + \sum_{i=1}^{n} w_i E[R_i].
\]
The variance in the portfolio value after one time period is

\[
\text{Var}(W) = \text{Var} \left( \sum_{i=1}^{n} w_i (1 + R_i) \right)
\]

\[
= \text{Var} \left( \sum_{i=1}^{n} w_i R_i \right)
\]

\[
= \sum_{i=1}^{n} \text{Var} (w_i R_i) + \sum_{i=1}^{n} \sum_{j \neq i} \text{Cov} (w_i R_i, w_j R_j)
\]

\[
= \sum_{i=1}^{n} w_i^2 \text{Var} (R_i) + \sum_{i=1}^{n} \sum_{j \neq i} w_i w_j \text{Cov} (R_i, R_j)
\].
Lemma

If $X$ is a lognormal random variable with drift parameter $\mu$ and volatility $\sigma^2$ and $K > 0$ is a constant then

$$\text{Cov} \left( X, (X - K)^+ \right) = \mathbb{E} \left[ X(X - K)^+ \right] - \mathbb{E} [X] \mathbb{E} [(X - K)^+] ,$$

where

$$\mathbb{E} \left[ X(X - K)^+ \right] = e^{2(\mu + \sigma^2)} \phi \left( w + 2\sigma \right) - Ke^{\mu + \sigma^2/2} \phi \left( w + \sigma \right),$$

with $w = (\mu - \ln K)/\sigma$. 
We will choose as our notion of an optimal portfolio, the portfolio whose value has the **minimum variance**.

Consider a portfolio consisting of a short position on a call option for stock A and a long position of \( n \) shares of stock B.

\[
P = C_A - nB.
\]

The variance in the value of the portfolio is

\[
\text{Var}(P) = E[(C_A - nB)^2] - E[C_A - nB]^2
\]

\[
= n^2 \text{Var}(B) - 2n \text{Cov}(C_A, B) + \text{Var}(C_A).
\]

Thus the minimum variance is achieved when

\[
N = \frac{\text{Cov}(C_A, B)}{\text{Var}(B)} = \rho(C_A, B) \sqrt{\frac{\text{Var}(C_A)}{\text{Var}(B)}}.
\]
Observations

1. If $\rho(C_A, B) = 1$ then $n = \sqrt{\frac{\text{Var}(C_A)}{\text{Var}(B)}}$.

2. If $\rho(C_A, B) \approx 0$ then stock B is a poor surrogate for stock A.

3. $n$ will decrease as $\text{Var}(B)$ increases.

4. If $A = B$ and the time to expiry is very short

$$n = \frac{\text{Cov}(C_A, A)}{\text{Var}(A)} = \frac{\text{Cov}(\Delta C_A, \Delta A)}{\text{Var}(\Delta A)}$$

$$= \frac{\text{Cov}\left(\frac{\partial C_A}{\partial A}, \Delta A, \Delta A\right)}{\text{Var}(\Delta A)} = \frac{\partial C_A}{\partial A} = \Delta.$$
A utility function assigns to the outcomes of an experiment, a value called the outcome’s utility.

Individual investors have differing utility functions corresponding to their affinity for taking investment risks.

The utility function plays a role in making rational investment decisions.
Suppose there are $n$ outcomes to an experiment

$$C_1 \leq C_2 \leq \cdots \leq C_n.$$

An investor can rank the outcomes in order of desirability. Suppose the outcomes have been ranked from least to most desirable as

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**Question:** How is utility assigned to an outcome?
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An investor can rank the outcomes in order of desirability. Suppose the outcomes have been ranked from least to most desirable as

\[
C_1 \leq C_2 \leq \cdots \leq C_n.
\]

**Question:** How is utility assigned to an outcome?  

**Answer:** Let the utility function be \( u(x) \), then assign \( u(C_1) = C_1 \) and \( u(C_n) = C_n \).
For $1 < i < n$ the investor is given a choice:

1. participate in a random experiment in which the probability of receiving $C_i$ is 1, or

2. participate in a random experiment where they receive $C_1$ with probability $\phi_i$ and receive $C_n$ with probability $1 - \phi_i$. 
Note:

- The expected value of the first experiment is $C_i$ and the expected value of the second experiment is $\phi_i C_1 + (1 - \phi_i) C_n$.
- By the Intermediate Value Theorem there exists $\phi_i \in [0, 1]$ such that

$$C_i = \phi_i C_1 + (1 - \phi_i) C_n$$

thus define $u(C_i) = \phi_i C_1 + (1 - \phi_i) C_n$. 

Remark: when \( u(C_i) = \phi_i C_1 + (1 - \phi_i) C_n \) the investor is indifferent to the choice.
Suppose an investor must choose between two different investment schemes. The union of all outcomes of the two schemes is the set

\[ \{ C_1, C_2, \ldots, C_n \} \]

The probability of receiving outcome \( C_i \) from the first scheme is \( p_i \) and the probability of receiving it from the second is \( q_i \).

If the utility of the \( i \)th outcome is \( u(C_i) \) then the investor will choose the first scheme if the expected value of its utility is greater than that of the second scheme:

\[
\sum_{i=1}^{n} p_i u(C_i) > \sum_{i=1}^{n} q_i u(C_i).
\]

In other words, the investor will choose the first scheme if the expected value of its utility is greater than that of the second scheme.
A Property of Utility Functions

The amount of extra utility that an investor experiences when $x$ is increased to $x + \Delta x$ is non-increasing.
Concave Functions

Definition

Function $f(t)$ is concave on an open interval $(a, b)$ if for every $x, y \in (a, b)$ and every $\lambda \in [0, 1]$ we have

$$\lambda f(x) + (1 - \lambda)f(y) \leq f(\lambda x + (1 - \lambda)y).$$

An investor whose utility function is concave is said to be risk-averse.

An investor with a linear utility function of the form $u(x) = ax + b$ with $a > 0$ is said to be risk-neutral.

An investor whose utility function increases more rapidly as the reward increases is said to be risk-loving.
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- An investor whose utility function increases more rapidly as the reward increases is said to be **risk-loving**.
Theorem

If \( f \in C^2(a, b) \) then \( f \) is concave on \((a, b)\) if and only if \( f''(t) \leq 0 \) for \( a < t < b \).
Proof ($f$ concave implies $f''(t) \leq 0$) (1 of 2)

If $f$ is concave on $(a, b)$ then by definition $f$ satisfies

$$\lambda f(x) + (1 - \lambda)f(y) \leq f(\lambda x + (1 - \lambda)y)$$

for every $x, y \in (a, b)$ and every $\lambda \in [0, 1]$.

- Assume $x < y$.
- If $w = \lambda x + (1 - \lambda)y$ and if $0 < \lambda < 1$ then
  
  $a < x < w < y < b$ and
  
  $$(1 - \lambda) [f(y) - f(w)] \leq \lambda [f(w) - f(x)].$$

- By the definition of $w$,

  $$1 - \lambda = \frac{w - x}{y - x} \quad \text{and} \quad \lambda = \frac{y - w}{y - x}.$$

- Substituting these expressions yields

  $$\frac{f(y) - f(w)}{y - w} - \frac{f(w) - f(x)}{w - x} \leq 0.$$
Proof ($f$ concave implies $f''(t) \leq 0$) (2 of 2)

\[
\frac{f(y) - f(w)}{y - w} - \frac{f(w) - f(x)}{w - x} \leq 0.
\]

Applying the Mean Value Theorem to each of the difference quotients of implies that for some $\alpha$ and $\beta$ satisfying with $x < \alpha < w < \beta < y$,

\[
f'(\beta) - f'(\alpha) \leq 0
\]

Using the Mean Value Theorem once more proves that for some $t$ with $\alpha < t < \beta$

\[
f''(t)(\beta - \alpha) \leq 0
\]

which implies $f''(t) \leq 0$. 

J. Robert Buchanan

Optimizing Portfolios
Jensen’s Inequality (Discrete Version)

Let $f$ be a concave function on the interval $(a, b)$, suppose $x_i \in (a, b)$ for $i = 1, 2, \ldots, n$, and suppose $\lambda_i \in [0, 1]$ for $i = 1, 2, \ldots, n$ with $\sum_{i=1}^{n} \lambda_i = 1$, then

$$\sum_{i=1}^{n} \lambda_i f(x_i) \leq f \left( \sum_{i=1}^{n} \lambda_i x_i \right).$$
Jensen’s Inequality (Discrete Version) Proof

Let $\mu = \sum_{i=1}^{n} \lambda_i x_i$ and note that since $\lambda_i \in [0, 1]$ for $i = 1, 2, \ldots, n$ and $\sum_{i=1}^{n} \lambda_i = 1$, then $a < \mu < b$. The equation of the line tangent to the graph of $f$ at $(\mu, f(\mu))$ is $y = f'(\mu)(x - \mu) + f(\mu)$. Since $f$ is concave on $(a, b)$ then

$$f(x_i) \leq f'(\mu)(x_i - \mu) + f(\mu) \quad \text{for } i = 1, 2, \ldots, n.$$ 

Therefore

$$\sum_{i=1}^{n} \lambda_i f(x_i) \leq \sum_{i=1}^{n} \left( \lambda_i \left[ f'(\mu)(x_i - \mu) + f(\mu) \right] \right)$$

$$= f'(\mu) \sum_{i=1}^{n} (\lambda_i x_i - \lambda_i \mu) + f(\mu) \sum_{i=1}^{n} \lambda_i$$

$$= f(\mu) = f \left( \sum_{i=1}^{n} \lambda_i x_i \right).$$
Let $\phi(t)$ be an integrable function on $[0, 1]$ and let $f$ be a concave function, then
\[
\int_0^1 f(\phi(t)) \, dt \leq f \left( \int_0^1 \phi(t) \, dt \right).
\]
Jensen’s Inequality (Continuous Version) Proof

Let $\alpha = \int_0^1 \phi(t) \, dt$ and let $y = f'(\alpha)(x - \alpha) + f(\alpha)$ be the equation of the tangent line at $(\alpha, f(\alpha))$. Since $f$ is concave then

$$f(\phi(t)) \leq f'(\alpha)(\phi(t) - \alpha) + f(\alpha),$$

which implies that

$$\int_0^1 f(\phi(t)) \, dt \leq \int_0^1 \left[ f'(\alpha)(\phi(t) - \alpha) + f(\alpha) \right] \, dt$$

$$= f(\alpha) + f'(\alpha) \int_0^1 (\phi(t) - \alpha) \, dt$$

$$= f(\alpha) = f \left( \int_0^1 \phi(t) \, dt \right).$$
Definition

The expected value of a utility function is called its expected utility.
The expected value of a utility function is called its **expected utility**.

**Example**

An investor is risk-averse with a utility function \( u(x) = x - x^2/25 \). The investor must choose between the following two “investments”:

- **A**: Flip a fair coin, if the coin lands heads up the investor receives $10, otherwise they receive nothing.
- **B**: Receive an amount $M with certainty.

Which do they choose?
A rational investor will select the investment with the greater expected utility.
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The expected utility for investment A is
\[ \frac{1}{2} u(10) + \frac{1}{2} u(0) = \frac{1}{2} \left( 10 - \frac{10^2}{25} \right) = 3. \]
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The expected utility for investment A is

$$\frac{1}{2}u(10) + \frac{1}{2}u(0) = \frac{1}{2} \left( 10 - \frac{10^2}{25} \right) = 3.$$  

The expected utility for B is $u(M) = M - \frac{M^2}{25}$. Thus the investor will choose the coin flip whenever

$$3 > M - \frac{M^2}{25}$$

Thus investment A is preferable to B whenever $M < $3.49.
Certainty Equivalent

Definition

The **certainty equivalent** is the minimum value $C$ of a random variable $X$ for which $u(C) = E[u(X)]$. 

Example

An investor is risk-averse with a utility function $u(x) = x - x^2/25$. The investor wishes to find the certainty equivalent $C$ for the following investment choice:

A: Flip a fair coin, if the coin lands heads up the investor receives $0 < X \leq 10$, otherwise they receive $0 < Y < X$.

B: Receive an amount $C$ with certainty.
The **certainty equivalent** is the minimum value $C$ of a random variable $X$ for which $u(C) = E[u(X)]$.

An investor is risk-averse with a utility function $u(x) = x - x^2/25$. The investor wishes to find the certainty equivalent $C$ for the following investment choice:

**A:** Flip a fair coin, if the coin lands heads up the investor receives $0 < X \leq 10$, otherwise they receive $0 < Y < X$.

**B:** Receive an amount $C$ with certainty.
The certainty equivalent and payoff of investment A must satisfy the following equation.

\[
C - \frac{C^2}{25} = \frac{1}{2} \left( X - \frac{X^2}{25} + Y - \frac{Y^2}{25} \right)
\]

\[
\left( C - \frac{25}{2} \right)^2 = \frac{1}{2} \left[ \left( X - \frac{25}{2} \right)^2 + \left( Y - \frac{25}{2} \right)^2 \right]
\]

\[
C = \frac{25}{2} - \frac{1}{\sqrt{2}} \sqrt{ \left( X - \frac{25}{2} \right)^2 + \left( Y - \frac{25}{2} \right)^2 }
\]
Solution (2 of 2)

J. Robert Buchanan

Optimizing Portfolios
We wish to examine the problem of allocating resources among potentially many different investments in an optimal fashion.

Consider a simple case:

- An investor has $x$ capital to invest.
- The investor allocates fraction $\alpha \in [0, 1]$ to an investment.
- The investment is structured such that an allocation of $\alpha x$ will earn $\alpha x$ with probability $p$ and lose $\alpha x$ with probability $1 - p$. 

J. Robert Buchanan

Optimizing Portfolios
The investor’s financial position after the investment is

\[ X = \begin{cases} 
  x(1 + \alpha) & \text{with probability } p, \\
  x(1 - \alpha) & \text{with probability } 1 - p.
\end{cases} \]

The allocation fraction \( \alpha \) will be optimal when the expected value of the utility is maximized.

\[
E[u(X)] = pu(x(1 + \alpha)) + (1 - p)u(x(1 - \alpha))
\]

\[
\frac{d}{d\alpha} E[u(X)] = pxu'(x(1 + \alpha)) - x(1 - p)u'(x(1 - \alpha))
\]

\[ 0 = pu'(x(1 + \alpha)) - (1 - p)u'(x(1 - \alpha)) \]

The appropriate value of \( \alpha \) will depend on the utility function \( u(t) \).
An investor has $x$ resources to allocate among $n$ investments.

The fraction invested in $i$ will be denoted $x_i$.

The return from investment $i$ will be $W_i = 1 + R_i$ where $R_i$ is the rate of return of investment $i$.

The general problem will then be that of determining $x_i$ for $i = 1, 2, \ldots, n$ such that

1. $0 \leq x_i \leq 1$ for $i = 1, 2, \ldots, n$, and
2. $\sum_{i=1}^{n} x_i = 1$,

and which maximizes the investor’s total expected utility $E[u(W)]$, where

$$W = \sum_{i=1}^{n} x_i W_i.$$

Assume $n$ is large and the $W_i$’s are not highly correlated. Thus the Central Limit Theorem implies $W$ is a normally distributed random variable.
Suppose \( u(x) = 1 - e^{-bx} \) where \( b > 0 \).

\[
E[u(W)] = E\left[1 - e^{-bW}\right] = 1 - E\left[e^{-bW}\right].
\]

The quantity \( e^{-bW} \) is a lognormal random variable.

\[
E\left[e^{-bW}\right] = e^{-bE[W] + b^2 \text{Var}(W)/2}
\]

which implies that

\[
E[u(W)] = 1 - e^{-b(E[W] - b\text{Var}(W)/2)}.
\]

Thus the expected utility is maximized when \( E[W] - b\text{Var}(W)/2 \) is maximized.
Suppose $b = 0.005$ and that an investor has $100$ to invest and will allocate $y$ dollars to security A and $100 - y$ dollars to B.

<table>
<thead>
<tr>
<th>Security</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [rate of return]</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>$\sqrt{\text{Var}}$ (rate of return)</td>
<td>0.20</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Assume that the correlation between the rates of return is $\rho = -0.35$.

\[
\begin{align*}
\text{E}[W] &= 100 + 0.16y + 0.18(100 - y) = 118 - 0.02y \\
\text{Var}(W) &= y^2(0.20)^2 + (100 - y)^2(0.24)^2 \\
&\quad + 2y(100 - y)(0.20)(0.24)(-0.35) \\
&= 0.04y^2 + 0.0576(100 - y)^2 - 0.0336y(100 - y)
\end{align*}
\]
The optimal portfolio is the one which maximizes

\[
E[W] - \frac{b}{2} \text{Var}(W) = 118 - 0.02y - 0.0025(0.04y^2 + 0.0576(100 - y)^2 - 0.0336y(100 - y)) = -0.000328y^2 + 0.0172y + 116.56.
\]

This occurs when \( y \approx 26.2195 \).

\[
E[W] \approx 117.476 \quad \text{Var}(W) \approx 276.049 \quad E[u(W)] \approx 0.442296.
\]
Theorem

Suppose that $0 \leq \alpha_i \leq 1$ will be invested in security $i$ for $i = 1, 2, \ldots, n$ subject to the constraint that $\alpha_1 + \alpha_2 + \cdots + \alpha_n = 1$. Suppose the rate of return of security $i$ is a random variable $R_i$ and that all the rates of return are mutually uncorrelated. The optimal, minimum variance portfolio described by the allocation vector $\langle \alpha_1^*, \alpha_2^*, \ldots, \alpha_n^* \rangle$, is the one for which

$$
\alpha_i^* = \frac{1}{\sigma_i^2} \frac{1}{\sum_{j=1}^{n} \frac{1}{\sigma_j^2}} \quad \text{for } i = 1, 2, \ldots, n,
$$

where $\sigma_i^2 = \text{Var} (R_i)$. 

J. Robert Buchanan
Optimizing Portfolios
Since the rates of return are uncorrelated, the variance of $W$ is

$$\text{Var} (W) = \sum_{i=1}^{n} \alpha_i^2 \sigma_i^2,$$

and is subject to the constraint $1 = \sum_{i=1}^{n} \alpha_i$. Applying the technique of Lagrange Multipliers yields the following equations.

$$\nabla \left( \sum_{i=1}^{n} \alpha_i^2 \sigma_i^2 \right) = \lambda \nabla \left( \sum_{i=1}^{n} \alpha_i \right)$$

$$\sum_{i=1}^{n} \alpha_i = 1$$

These equations are equivalent to respectively:

$$2 \alpha_i \sigma_i^2 = \lambda \quad \text{for } i = 1, 2, \ldots, n, \text{ and}$$

$$\sum_{i=1}^{n} \alpha_i = 1.$$
Solving for $\alpha_i$ in the first equation and substituting into the second equation determines that

$$\lambda = \frac{2}{\sum_{j=1}^{n} \frac{1}{\sigma_j^2}}.$$

Substituting this expression for $\lambda$ into the first equation yields

$$\alpha_i = \frac{1}{\sigma_i^2} \frac{1}{\sum_{j=1}^{n} \frac{1}{\sigma_j^2}} \text{ for } i = 1, 2, \ldots, n.$$
Including the Effects of Borrowing

Assume:

- \( \mathbf{w} = \langle w_1, w_2, \ldots, w_n \rangle \) represents a portfolio of investments.
- \( R_i \) represents the rate of return on investing \( w_i \) in the \( i^{th} \) security.
- Investments are purchased by borrowing money which must be paid back in one time unit at simple interest rate \( r \).

Then the net wealth generated by the portfolio is

\[
R(\mathbf{w}) = \sum_{i=1}^{n} w_i(1 + R_i) - (1 + r) \sum_{i=1}^{n} w_i = \sum_{i=1}^{n} w_i(R_i - r).
\]

The expected value and variance of the net wealth generated by the portfolio are

\[
r(\mathbf{w}) = \mathbb{E}[R(\mathbf{w})]
\]
\[
\sigma^2(\mathbf{w}) = \text{Var}(R(\mathbf{w})).
\]
Lemma

Assuming the rates of return on the securities are uncorrelated, the optimal portfolio generating an expected unit amount of net wealth with the minimum variance in the net wealth is

\[ \mathbf{w}^* = \left\langle \frac{r_1 - r}{\sigma_1^2}, \frac{r_2 - r}{\sigma_2^2}, \ldots, \frac{r_n - r}{\sigma_n^2} \right\rangle \]

where \( r_i = \mathbb{E}[R_i] \) and \( \sigma_i^2 = \text{Var}(R_i) \) for \( i = 1, 2, \ldots, n \).
The following result indicates to an investor how portions of a portfolio should be invested so as to minimize the variance in the wealth generated.

**Theorem (Portfolio Separation Theorem)**

*If $b$ is any positive scalar, the variance of all portfolios with expected wealth generated equal to $b$ is minimized by portfolio $bw^*$ where*

$$w^* = \left\langle \frac{r_1-r}{\sigma_1^2}, \frac{r_2-r}{\sigma_2^2}, \ldots, \frac{r_n-r}{\sigma_n^2} \right\rangle = \left( \frac{1}{\sum_{j=1}^{n} \frac{(r_j-r)^2}{\sigma_j^2}} , \frac{1}{\sum_{j=1}^{n} \frac{(r_j-r)^2}{\sigma_j^2}} , \ldots , \frac{1}{\sum_{j=1}^{n} \frac{(r_j-r)^2}{\sigma_j^2}} \right)$$
Suppose \( x \) is a portfolio for which \( r(x) = b \), then

\[
\frac{1}{b} r(x) = r \left( \frac{1}{b} x \right) = 1.
\]

Thus \( \frac{1}{b} x \) is a portfolio with unit expected rate of return. For the portfolio \( w^* \),

\[
\sigma^2(bw^*) = b^2 \sigma^2(w^*) \leq b^2 \sigma^2 \left( \frac{1}{b} x \right) = \sigma^2(x).
\]
Suppose an investor divides a unit of resources between a risky and a risk-free investment

1. \( x \in [0, 1] \) is invested in a security whose rate of return is \( R_S \), and

2. \( 1 - x \) earns interest in a safe savings account at rate \( r_f \).

The rate of return on the portfolio is

\[
R = (1 - x)r_f + xR_S,
\]

and the expected rate of return is

\[
E[R] = r = r_f + (r_S - r_f)x
\]

where \( r_S = E[R_S] \).

\[
\text{Var}(R) = \sigma^2 = x^2 \text{Var}(R_S) = x^2 \sigma^2_S
\]
Combining the equations for $E[R]$ and $\text{Var}(R)$ and eliminating $x$ produces

$$r = r_f + \frac{r_S - r_f}{\sigma_S} \sigma$$

If instead of a single security $x$ was invested evenly throughout the market then we obtain the equation for the **capital market line**.

$$r = r_f + \frac{r_M - r_f}{\sigma_M} \sigma$$
Suppose an investor wishes to weigh the return on an investment against the risk associated with the investment.

- \( R_i \): return on investment in security \( i \)
- \( R_M \): return on the entire market
- \( x \): fraction of unit wealth invested in security \( i \)
- \( 1 - x \): fraction of unit wealth invested in market

The rate of return on the portfolio is

\[
R = xR_i + (1 - x)R_M,
\]

with

\[
\begin{align*}
E[R] &= xE[R_i] + (1 - x)E[R_M] \\
\text{Var}(R) &= x^2\text{Var}(R_i) + (1 - x)^2\text{Var}(R_M) + 2x(1 - x)\text{Cov}(R_i, R_M).
\end{align*}
\]
The expected value and variance of $R$ can be re-written as

\[
\begin{align*}
 r &= x r_i + (1 - x) r_M \\
 \sigma^2 &= x^2 \sigma_i^2 + (1 - x)^2 \sigma_M^2 + 2x(1 - x) \rho_{i,M} \sigma_i \sigma_M.
\end{align*}
\]

where $r = \mathbb{E}[R]$, $r_i = \mathbb{E}[R_i]$, $r_M = \mathbb{E}[R_M]$, $\sigma^2 = \text{Var}(R)$, $\sigma_i^2 = \text{Var}(R_i)$, and $\sigma_M^2 = \text{Var}(R_M)$.
These two equations give us the parametric form of a parabola in the $\sigma r$-plane.
Using this tangency relationship we can determine that

\[ r_i - r_f = \frac{\rho_i,M \sigma_i}{\sigma_M} (r_M - r_f) = \beta_i (r_M - r_f). \]

The CAPM can be interpreted as stating that the excess rate of return of security \( i \) above the risk-free interest rate is proportional to the excess rate of return of the market above the risk-free interest rate.
Suppose the risk-free interest rate is 5% per year, the return on the market is 9% per year, and the volatility in the market is 35% per year. Suppose further that the covariance between the return on a particular stock and the return on the market is 0.10. Estimate the return on the stock.

Using the CAPM, 

\[ \beta = \frac{\text{Cov}(R, R_M)}{\sigma^2_M} = 0.10 \times (0.35)^2 = 0.08153 \]

which implies 

\[ r = r_f + \beta (r_M - r_f) = 0.5 + 0.8153 (0.09 - 0.05) = 0.0827 \]

or 8.27%.
Example

Suppose the risk-free interest rate is 5% per year, the return on the market is 9% per year, and the volatility in the market is 35% per year. Suppose further that the covariance between the return on a particular stock and the return on the market is 0.10. Estimate the return on the stock.

Using the CAPM,

\[ \beta = \frac{\text{Cov}(R, R_M)}{\sigma^2_M} = \frac{0.10}{(0.35)^2} = 0.8153 \]

which implies

\[ r = r_f + \beta (r_M - r_f) = 0.05 + 0.8153(0.09 - 0.05) = 0.0827 \]

or 8.27%.