Foundations of Financial Economics
Multi-period finance economies

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May 7, 2021

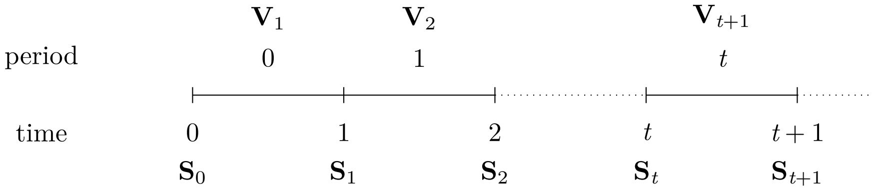
Topics for today

- Arbitrage asset pricing
- Equilibrium asset pricing for a homogeneous household economy: the zero initial wealth case
- Equity premium puzzle again
- Non-zero initial wealth case

Arbitrage asset pricing

The structure of the asset market

There are two stochastic processes: $\{\mathbf{V}_t\}_{t=1}^{T}$ and $\{\mathbf{S}_t\}_{t=0}^{T-1}$



- at every time $t = 0, \ldots, T-1$ (not just at $t = 0$ as before) K assets traded at the vector of price $\mathbf{S}_t$ is set
- asset deliver payoffs $\mathbf{V}_{t+1}$ in period $t = 0, \ldots, T-1$, unknown at the time t of price determination

The price process

- The price process is $\{\mathbf{S}_t\}_{t=1}^{T} = \{\mathbf{S}_0, \mathbf{S}_1, \ldots, \mathbf{S}_t, \ldots, \mathbf{S}_{T-1}\}$, where

$$\mathbf{S}_t = (S_t^1, \ldots, S_t^K), \text{ for } S_t^j = \begin{pmatrix} s_{t,1}^j \\ \ldots \\ s_{t,s}^j \\ \ldots \\ s_{t,N_t}^j \end{pmatrix}$$

conditional on the information at time $t = 0$

- or, expanding, the possible realizations for the price at at time $t > 0$ are

$$\mathbf{S}_t = \begin{pmatrix} s_{t,1}^1 & \ldots & s_{t,1}^j & \ldots & s_{t,1}^K \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ s_{t,s}^1 & \ldots & s_{t,s}^j & \ldots & s_{t,s}^K \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ s_{t,N_t}^1 & \ldots & s_{t,N_t}^j & \ldots & s_{t,N_t}^K \end{pmatrix}$$

The payoff process

- The payoff process $\{\mathbf{V}_t\}_{t=1}^{T} = \{\mathbf{V}_1, \mathbf{V}_2, \dots, \mathbf{V}_t, \dots, V_T\}$, where

$$\mathbf{V}_t = (V_t^1, \dots, V_t^K), \text{ for } V_t^j = \begin{pmatrix} v_{t,1}^j \\ \dots \\ v_{t,s}^j \\ \dots \\ v_{t,N_t}^j \end{pmatrix}$$

conditional on the information at time $t = 0$

- or, expanding, the possible realizations for the payoff at time t are

$$\mathbf{V}_t = \begin{pmatrix} v_{t,1}^1 & \dots & v_{t,1}^j & \dots & v_{t,1}^K \\ \dots & \dots & \dots & \dots & \dots \\ v_{t,s}^1 & \dots & v_{t,s}^j & \dots & v_{t,s}^K \\ \dots & \dots & \dots & \dots & \dots \\ v_{t,N_t}^1 & \dots & v_{t,N_t}^j & \dots & v_{t,N_t}^K \end{pmatrix}$$

The structure of the asset market

The return process results: $\{\mathbf{R}_t\}_{t=1}^{T} = \{\mathbf{R}_1, \ldots, \mathbf{R}_t, \ldots, R_T\}$

period	0	1		t	
time	0	1	2	t	$t+1$
		$\mathbf{R}_1$	$\mathbf{R}_2$	$\mathbf{R}_t$	$\mathbf{R}_{t+1}$

- where the returns for every asset $\mathbf{R}_t = (R_t^1 \ \ldots, R_t^K)$,
- where $R_t^j = (R_{t,1}^j, \ldots, R_{t,N_t}^j)^\top$
- the return of asset j at time t is $R_t^j = \dfrac{V_t^j + S_t^j}{S_{t-1}^j}$
- is determined after the observation of price S_t^j, i.e., after being sold at the current market price.

Example

- Two-state binomial tree and $T = 3$ (information conditional at time $t = 0$)
- Two assets: a and b
- Prices and payoffs processes
  - at time $t = 0$ only prices are observed $\mathbf{S}_0 = (S_0^a, S_0^b)$
  - at time $t = 1$, $\mathbf{V}_1 = \begin{pmatrix} V_{1,1}^a & V_{1,1}^b \\ V_{1,2}^a & V_{1,2}^b \end{pmatrix}$ and $\mathbf{S}_1 = \begin{pmatrix} S_{1,1}^a & S_{1,1}^b \\ S_{1,2}^a & S_{1,2}^b \end{pmatrix}$
  - at time $t = 2$

$$\mathbf{V}_2 = \begin{pmatrix} V_{2,1}^a & V_{2,1}^b \\ V_{2,2}^a & V_{2,2}^b \\ V_{2,3}^a & V_{2,3}^b \\ V_{2,4}^a & V_{2,4}^b \end{pmatrix}, \ \mathbf{S}_2 = \begin{pmatrix} S_{2,1}^a & S_{2,1}^b \\ S_{2,2}^a & S_{2,2}^b \\ S_{2,3}^a & S_{2,3}^b \\ S_{2,4}^a & S_{2,4}^b \end{pmatrix}$$

  - at terminal time $t = 3$

$$\mathbf{V}_3 = \begin{pmatrix} V_{3,1}^a & V_{3,1}^b \\ \dots & \dots \\ V_{3,8}^a & V_{3,8}^b \end{pmatrix}$$

Arbitrage asset pricing

Stochastic discount factor: intertemporal form

Definition

A ***stochastic discount factor*** *(SDF) is a process* $\{M_t\}_{t=0}^{T-1}$*, such that,* ***for any asset*** $j = 1, \dots, K$*:*

1. M_t *is* $\mathcal{F}_t$*-measurable (v.g., has a tree structure) ,*
2. $M_0 = m_0 = 1$
3. *satisfies*

$$\boxed{M_t S_t^j = \mathbb{E}_t \left[\sum_{\tau=t+1}^{T} M_\tau V_\tau^j \right], \; for\ t = 0, \dots, T-1}$$

(i.e) the value of any asset j at time t is equal to the (conditional) mathematical expectation of the value of its future payoffs

Arbitrage asset pricing

Stochastic discount factor: intertemporal form

Observations:

1. We say this is SDF definition is in the **intertemporal form**
2. the meaning of the conditional expectation $\mathbb{E}_t[.]$ is

$$M_t S_t^j = \mathbb{E}_t \left[\sum_{\tau=t+1}^{T} M_\tau V_\tau^j \right] = \mathbb{E} \left[\sum_{\tau=t+1}^{T} M_\tau V_\tau^{j,t} \,\middle|\, S^{j,t}, V^t \right], \text{ for any } j = 1, \dots$$

where $S^{j,t} = \{S_0^j, S_1^j, \dots S_t^j\}$ and $V^{j,t} = \{V_1^j, \dots V_t^j\}$ are the histories of the asset prices and payoffs of asset t up until time t

Arbitrage asset pricing

Stochastic discount factor: recursive form

Proposition

The stochastic discount factor can be equivalently defined in the ***recursive from***

$$\boxed{M_t S_t^j = \mathbb{E}_t \left[M_{t+1}(S_{t+1}^j + V_{t+1}^j) \right], \textit{ for any } j = 1, \ldots, K}$$

- **Intuition**: the stochastic discount factor is a stochastic process $\{M_t\}$, that equalizes the **value** of the asset price in period t with the conditional expected value of the **value** of the income in period $t+1$ (the income is equal to the payoff plus the anticipated market price)

Arbitrage asset pricing

Stochastic discount factor: recursive form

Proof:

- using the definition of intertemporal form and expanding

$$M_t S_t^j = \mathbb{E}_t \left[M_{t+1} V_{t+1}^j + \sum_{\tau=t+2}^{T} M_\tau V_\tau^j \right]$$

- by the law of iterated expectations

$$\mathbb{E}_t \left[M_{t+1} V_{t+1}^j + \sum_{\tau=t+2}^{T} M_\tau V_\tau^j \right] = \mathbb{E}_t \left[M_{t+1} V_{t+1}^j + \mathbb{E}_{t+1} \left[\sum_{\tau=t+2}^{T} M_\tau V_\tau^j \right] \right]$$

- but

$$M_{t+1} S_{t+1}^j = \mathbb{E}_{t+1} \left[\sum_{\tau=t+2}^{T} M_\tau V_\tau^j \right],$$

- then $M_t S_t^j = \mathbb{E}_t \left[M_{t+1} V_{t+1}^j \right] + \mathbb{E}_t \left[M_{t+1} S_{t+1}^j \right]$

Arbitrage asset pricing

Stochastic discount factor and the rate of return

Proposition

The stochastic discount factor can be equivalently defined in the ***recursive from*** *using the definition of the return of an asset*

$$\boxed{M_t = \mathbb{E}_t\left[M_{t+1}R_{t+1}^j\right],\ \textit{for any}\ j = 1, \ldots, K}$$

- **Intuition**: the stochastic discount factor is a stochastic process $\{M_t\}$, that equalizes the **value** of the return of an investment (or loan) to be collected (or payed) at time $t+1$, to the price of money, conditional on the information at time t

Portfolios and income

Stochastic processes for portfolios and income: $\{\boldsymbol{\theta}_t\}_{t=1}^{T-1}$ and $\{Z_t\}_{t=0}^{T}$

		z_0^θ		Z_1^θ				Z_t^θ	
period		0		1				t	
time	0		1		2		t		$t+1$
	$\boldsymbol{\theta}_0 = \mathbf{0}$	$\boldsymbol{\theta}_1$		$\boldsymbol{\theta}_2$				$\boldsymbol{\theta}_{t+1}$	

- at every time $t = 0, \dots, T-1$ (not just at $t = 0$ as before) a portfolio $\boldsymbol{\theta}_{t+1} = (\theta_{t+1}^1, \dots, \theta_{t+1}^K)$ can be detained
- it generates an income in period $t = 0, \dots, T$, Z_t^θ

Arbitrage asset pricing

Transactions strategy

- The **income** stream $\{Z_t^\theta\}_{t=0}^T$ where (zero initial wealth) generated by a transactions strategy $\{\boldsymbol{\theta}_t\}_{t=1}^T$ is

$$
\begin{aligned}
z_0^\theta &= -\theta_1 S_0 = -\sum_{j=1}^K \theta_1^j S_0^j \\
&\dots \\
Z_t^\theta &= \theta_t(S_t + V_t) - \theta_{t+1} S_t = \sum_{j=1}^K \left(\theta_t^j(S_t^j + V_t^j) - \theta_{t+1}^j S_t^j\right), \\
Z_T^\theta &= \theta_T V_T = \sum_{j=1}^K \theta_T^j V_T^j
\end{aligned}
$$

- where $Z_t^\theta \in \mathbb{R}^{N_t}$ is $\mathcal{F}_t$-measurable, i.e.

$$
Z_t^\theta = (z_{t,1}^\theta, \dots, z_{t,s}^\theta, \dots, z_{t,N_t}^\theta)
$$

Arbitrage asset pricing

Transactions strategy

Definition

A ***transactions strategy*** *is a sequence of portfolios* $\{\boldsymbol{\theta}_{t+1}\}_{t=0}^{T-1}$, *with* $\boldsymbol{\theta}_{t+1} = (\theta^1_{t+1} \ldots \theta^K_{t+1})$, *where* θ^j_{t+1} *is* $\mathcal{F}_t$*-measurable, generating an* ***income*** *stream* $\{Z^\theta_t\}_{t=0}^{T} = \{z^\theta_0, Z^\theta_1, \ldots, Z^\theta_T\}$.

Definition

If $z^\theta_0 = \ldots = Z^\theta_t = \ldots = Z^\theta_T = \mathbf{0}$ *we say the transactions strategy is* ***self-financed***.

Definition

There is **absence of arbitrage opportunities** *if there is a* ***positive process*** $\{M_t\}_{t=0}^{T-1}$ *such that the income stream* $\{Z_t^\theta\}_{t=0}^{T}$*, generated by the transaction strategy* $\{\boldsymbol{\theta}_{t+1}\}_{t=0}^{T-1}$*, satisfies*

$$\boxed{\mathbb{E}_0\left[\sum_{t=0}^{T} M_t Z_t^\theta\right] = 0}$$

Intuition: there are no arbitrage opportunities if, with a **zero initial investment**, the expected value of the present value of any transaction strategy is zero, if the discount factor is positive.

Arbitrage asset pricing

Absence of arbitrage opportunities

Proposition

A necessary condition for the absence of arbitrage opportunities is that:

1. *The terminal price satisfies* $M_T S_T = 0$ *if* T *is finite;*
2. *ruling-out speculative bubbles condition holds:* $\lim_{t \to \infty} M_t S_t = 0$ *if* $T = \infty$

Arbitrage asset pricing

Absence of arbitrage opportunities

Proof (assuming $K=1$):

- use the definition of stochastic discount factor (in the recursive form)
$$-M_0 Z_0^{\theta} = M_0\theta_1 S_0 = \mathbb{E}_0\left[M_1\theta_1(S_1+V_1)\right]$$
- use a little trick, introducing $\pm M_1\theta_2 S_1$;
$$\begin{aligned}\mathbb{E}_0\left[M_1\theta_1(S_1+V_1)\right] &= \mathbb{E}_0\left[M_1\theta_1(S_1+V_1)\pm M_1\theta_2 S_1\right]= \\ &= \mathbb{E}_0\left[M_1 Z_1^{\theta}+M_1\theta_2 S_1\right]\end{aligned}$$
- use the definition of stochastic discount factor and the law of iterated expectations
$$\begin{aligned}\mathbb{E}_0\left[M_1 Z_1^{\theta}+M_1\theta_2 S_1\right] &= \mathbb{E}_0\left[M_1 Z_1^{\theta}+\mathbb{E}_1\left[M_2\theta_2(S_2+V_2)\right]\right] \\ &= \mathbb{E}_0\left[M_1 Z_1^{\theta}+M_2\theta_2(S_2+V_2)\right]\end{aligned}$$

Arbitrage asset pricing

Absence of arbitrage opportunities

Proof (assuming $K = 1$ continuation):

- by repeatedly using the previous steps we arrive at

$$-M_0 Z_0^\theta = \mathbb{E}_0 \left[\sum_{t=1}^{T} M_t Z_t^\theta + M_T \theta_{t+1} S_T \right]$$

- then

$$\mathbb{E}_0 \left[\sum_{t=0}^{T} M_t Z_t^\theta \right] = 0$$

  only if $M_T S_T = 0$

Application 1: zero payoffs

Absence of arbitrage opportunities

- **Zero payoffs (or no dividends case)**: Assume that there are no dividends, i.e., $V_t = \mathbf{0}$ for any $t = 1, \ldots, T$.
- If there are no arbitrage opportunities then

$$M_t S_t^j = \mathbb{E}_t \left[M_{t+1} S_{t+1}^j \right]$$

- therefore:

Proposition

For a zero dividend process, the process $\{M_t S_t\}_{t=0}^{T-1}$ ***is a martingale under measure*** $\mathbb{P}$,

Arbitrage asset pricing

Fundamental theorem

Proposition

For a zero-dividend asset, absence of arbitrage opportunities is equivalent to the existence of an equivalent probability measure $\mathbb{Q}$ *such that* $\{S_t\}_{t=0}^{T-1}$ *is a martingale under* $\mathbb{Q}$*, that is*

$$S_t^j = \mathbb{E}_t^{\mathbb{Q}}[S_{t+1}^j]$$

Arbitrage asset pricing

Fundamental theorem

Sketch of proof

- Let us define the **conditional** stochastic discount factor

$$M_{t+1|t} \equiv \frac{M_{t+1}}{M_t}$$

- Then if there are no arbitrage opportunities (because M_t is $\mathbb{F}_t$-measurable)

$$S_t^j = \mathbb{E}_t[M_{t+1|t} S_{t+1}^j]$$

- This is valid for the degenerate process $\{\mathbf{1}\}_{t=0}^T = \{\mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}\}$, then

$$1 = \mathbb{E}_t[M_{t+1|t}]$$

$$S_t^j = \mathbb{E}_t[M_{t+1|t} S_{t+1}^j] = \frac{\mathbb{E}_t[M_{t+1|t} S_{t+1}^j]}{\mathbb{E}_t[M_{t+1|t}]} = \mathbb{E}_t^{\mathbb{Q}}[S_{t+1}^j]$$

- from the Radon-Nikodym theorem $\mathbb{Q}$ is an equivalent martingale measure.

Observe that $\{M_t\}$ is also a martingale, under measure $\mathbb{Q}$ because

$$M_t = \mathbb{E}_t^{\mathbb{Q}}[M_{t+1}]$$

Application 2: positive payoffs

- **Positive payoffs (or positive dividends case)**: if asset j pays a positive dividend, that is $V_t^j \geq \mathbf{0}$ is a positive vector, then

$$\mathbb{E}_t^{\mathbb{Q}}[S_{t+1}^j + V_{t+1}^j] \geq \mathbb{E}_t^{\mathbb{Q}}[S_{t+1}^j]$$

- Then $\{S_t\}$ is a **submartingale** under measure $\mathbb{Q}$

$$S_t^j \geq \mathbb{E}_t^{\mathbb{Q}}[S_{t+1}^j]$$

Proposition

For a positive-dividend asset, absence of arbitrage opportunities is equivalent to the existence of an equivalent probability measure $\mathbb{Q}$ such that $\{S_t\}_{t=0}^{T-1}$ is a sub-martingale under $\mathbb{Q}$, that is

$$S_t^j \geq \mathbb{E}_t^{\mathbb{Q}}[S_{t+1}^j]$$

Application 3: Existence of a risk-free asset

- Consider a bond, issued at every time $t = 0, \ldots, T-1$, with the maturity of one period and paying a (deterministic) payoff with unit face value
- Then

$$S_t^f = \frac{1}{1 + r_{t+1}}, \;\; V_{t+1}^f = \mathbf{1}, \;\; V_{t+2}^f = \mathbf{0}, \ldots \; V_T^f = \mathbf{0}$$

- If there are no arbitrage opportunities then

$$\frac{1}{1 + r_{t+1}} = \mathbb{E}_t \left[M_{t+1|t} \right].$$

Application 3: Existence of a risk-free asset

Proposition

Assume there are no arbitrage opportunities and there is a risk-free asset with the (deterministic) return process $\{R_t^f\}_{t=1}^T$*. Then there is a probability process* $\mathbb{Q}$ *such that the return for asset* j *satisfies*

$$\boxed{R_{t+1}^f = \mathbb{E}_t^{\mathbb{Q}}\left[R_{t+1}^j\right], \textit{ for any } j = 1, \dots K, \textit{for any } t = 0, \dots T}$$

Application 3: Existence of a risk-free asset

- Proof: for any other risky asset, j, we can write

$$\begin{aligned}
\mathbb{E}_t^{\mathbb{Q}}\left[S_{t+1}^j + V_{t+1}^j\right] &= \frac{\mathbb{E}_t\left[M_{t+1|t}\left(S_{t+1}^j + V_{t+1}^j\right)\right]}{\mathbb{E}_t\left[M_{t+1|t}\right]} = \\
&= (1 + r_{t+1})\,\mathbb{E}_t\left[M_{t+1|t}\left(S_{t+1}^j + V_{t+1}^j\right)\right] = \\
&= (1 + r_{t+1})\,S_t^j
\end{aligned}$$

- Then

$$S_t^j = \frac{1}{1 + r_{t+1}}\mathbb{E}_t^{\mathbb{Q}}\left[S_{t+1}^j + V_{t+1}^j\right]$$

- Dividing by S_t^j we find

$$R_{t+1}^f = \mathbb{E}_t^{\mathbb{Q}}\left[R_{t+1}^j\right]$$

- It can also be proved that

$$S_t^j = \mathbb{E}_t^{\mathbb{Q}} \left[\sum_{\tau=t+1}^{T} D_{t+1,\tau} \, V_\tau^j \right]$$

the asset price at time t is the conditional expected value of the present value of the future payoffs;

- where the discount factor is

$$D_{t+1,\tau} = \prod_{h=t+1}^{\tau} \frac{1}{1+r_h}, \; \tau \geq t+1.$$

- Exercise: prove this.

Equilibrium asset pricing

Equilibrium asset pricing

Real part of the economy: resources

- There is a **given** sequence of endowments

$$Y^T \equiv \{ Y_t \}_{t=0}^{T} = \{ Y_0, Y_1, \dots, Y_t, \dots, Y_T \}$$

- where Y_t is $\mathcal{F}_t$- mensurable, such that

$$Y_t = \begin{pmatrix} y_{t,1} \\ \dots \\ y_{t,N_t} \end{pmatrix}$$

Equilibrium asset pricing

Real part of the economy: preferences and distribution

- households choose a contingent-consumption sequence belonging to the set

$$C^T \equiv \{C_t\}_{t=0}^T = \{C_0, C_1, \dots, C_t, \dots, C_T\}$$

where C_t is $\mathcal{F}_t$- mensurable,

- through an intertemporal von-Neumman-Morgenstern functional

$$\mathbb{E}_0\left[\sum_{t=0}^{T}\beta^t u(C_t)\right]$$

- expansion of the utility functional

$$\begin{aligned}\mathbb{E}_0\left[\sum_{t=0}^{T}\beta^t u(C_t)\right] &= \sum_{t=0}^{T}\beta^t \mathsf{P}_t u(C_t) = \\ &= u(C_0) + \beta\mathsf{P}_1 u(C_1) + \dots + \beta^t\mathsf{P}_t u(C_t) + \dots + \beta^T\mathsf{P}\end{aligned}$$

where

$$\mathsf{P}_t u(C_t) = \sum_{s=1}^{N_t}\pi_{t,s} u(c_{t,s})$$

There are assets markets with the structure we have just presented, opening at every time $t \in \{0, \ldots, T\}$

Equilibrium asset pricing: zero initial wealth

Assumption: the level of initial net wealth is zero $a_0 = 0$

Consequence: we can transform the household problem in a finance economy into the household problem in an equivalent AD economy

Non-zero initial wealth: we have to apply other methods for solving the household-investor problem (v.g, dynamic programming or optimal control)

Flow and stock accounting

Adaptoing the timing

		$c_0 = y_0 + a_0 + z_0^\theta$		$C_1 = Y_1 + Z_1^\theta$				$C_t = Y_t + Z_t^\theta$	
period		0		1				t	
time	0		1		2		t		$t+1$
	a_0		$a_1 = z_0^\theta$		$A_2 = Z_1^\theta$		$A_t = Z_{t-1}^\theta$		$A_{t+1} = Z_t^\theta$

Equilibrium asset pricing: Zero initial wealth

Radner or sequential general equilibrium

Definition

The **Radner or sequential general equilibrium** *is defined by the processes* $\{C_t\}_{t=0}^{T}$, $\{\boldsymbol{\theta}_t\}_{t=1}^{T}$ *and* $\{\S_t\}_{t=0}^{T-1}$ *such that,* ***given*** *the processes of endowments* $\{Y_t\}_{t=0}^{T}$ *and payoffs* $\{\mathbf{V}_t\}_{t=1}^{T}$*:*
(1) the household solves his ***consumption-portfolio problem****, with rational expectations regarding future asset prices, and*
(2) the ***markets clear****,*

$$
\begin{aligned}
C_t &= Y_t,\ t = 0, \ldots, T \\
\boldsymbol{\theta}_t &= 0,\ t = 1, \ldots, T.
\end{aligned}
$$

Equilibrium asset pricing: Zero initial wealth

The (sequential) household-investor problem

Find the process for consumption $\{C_t\}_{t=0}^{T}$ and a transactions' strategy $\{\theta_t\}_{t=1}^{T}$

- that maximizes the value functional

$$V_0(\{C_t\},\{\theta_t\}) \equiv \mathbb{E}_0\left[\sum_{t=0}^{T}\beta^t u(C_t)\right]$$

- subject to the sequential budget constraints

$$\begin{aligned}
c_0 + \sum_{j=1}^{K}\theta_1^j S_0^j &\leq y_0 \\
&\cdots \\
C_t + \sum_{j=1}^{K}\theta_{t+1}^j S_t^j &\leq Y_t + \sum_{j=1}^{K}\theta_t^j(S_t^j + V_t^j),\ t = 1,\ldots,T-1\ (\mathcal{F}_t - \text{adapt} \\
&\cdots \\
C_T &\leq Y_T + \sum_{j=1}^{K}\theta_T^j V_T^j\ (\mathcal{F}_T - \text{adapted})
\end{aligned}$$

Equilibrium asset pricing: Zero initial wealth

The (sequential) household problem

- We can write the sequence of budget constraints equivalently as

$$
\begin{aligned}
C_0 &\leq Y_0 + Z_0^\theta \\
&\dots \\
C_t &\leq Y_t + Z_t^\theta,\ t = 1, \dots, T-1 \ (\mathcal{F}_t - \text{adapted}) \\
&\dots \\
C_T &\leq Y_T + Z_T^\theta \ (\mathcal{F}_T - \text{adapted})
\end{aligned}
$$

  where Z_t^θ is the income generated at time t by the transaction strategy $\{\theta_t\}_{t=1}^T$.

- If the utility function $u(.)$ displays no-satiation the constraints hold with equality in the optimum.

Equilibrium asset pricing: Zero initial wealth

Equivalent simultaneous household problem

- **If there are no arbitrage opportunities**, then there is stochastic discount factor process $\{M_t\}_{t=0}^{T-1}$, such that

$$-\mathbb{E}_0\left[\sum_{t=0}^{T} M_t Z_t^\theta\right] = \mathbb{E}_0\left[\sum_{t=0}^{T} M_t(Y_t - C_t)\right] = 0.$$

- Then, the household's problem is (the same as in the AD economy)

$$\max_{\{C_t\}_{t=0}^{T}} \mathbb{E}_0\left[\sum_{t=0}^{T} \beta^t u(C_t)\right] \text{ s.t } \mathbb{E}_0\left[\sum_{t=0}^{T} M_t(Y_t - C_t)\right] = 0$$

- We already found the f.o.c

$$u'(c_0)M_t = \beta^t u'(C_t), \ (\mathcal{F}_t - \text{adapted})$$

Equilibrium asset pricing: Zero initial wealth

Equilibrium stochastic discount factor

- The household arbitrage condition and the market equilibrium conditions

$$\begin{cases} u'(c_0)M_t = \beta^t u'(C_t) & t = 1, \dots, T \\ C_t = Y_t & t = 0, \dots, T \end{cases}$$

- imply that, at equilibrium, as in the AD economy

$$\boxed{M_t = \beta^t \frac{u'(Y_t)}{u'(Y_0)} \ (\mathcal{F}_t - \text{adapted})}$$

- In terms of the possible realizations

$$M_t = \begin{pmatrix} m_{t,1} \\ \dots \\ m_{t,N_t} \end{pmatrix}, \ t = 0, \dots, T-1$$

  where

$$m_{ts} = \beta^t \frac{u'(y_{ts})}{u'(y_0)}, \text{ for } s = 1, \dots, N_t, \text{and}, \ t = 0, \dots T-1.$$

Equilibrium asset pricing: Zero initial wealth

- If there are no arbitrage opportunities, we proved that, for any asset j

$$M_t S_t^j = \mathbb{E}_t\left[M_{t+1}(V_{t+1}^j + S_{t+1}^j)\right], \ \ j = 1, \dots, K$$

- Then the **GE equilibrium** asset pricing is

$$\boxed{u'(Y_t) S_t^j = \beta \mathbb{E}_t\left[u'(Y_{t+1})(V_{t+1}^j + S_{t+1}^j)\right], \ \ j = 1, \dots, K}$$

- determines asset price process $\{S_t^j\}$ given the processes $\{V_t^j\}$ and $\{Y_t\}$.

Equilibrium asset pricing: Zero initial wealth

Equivalent representations:

1. The **equilibrium rate of return** for asset j is determined from

$$\boxed{\mathbb{E}_t\left[M_{t+1|t}R^j_{t+1}\right] = 1}$$

where the **equilibrium recursive stochastic discount factor** is

$$M_{t+1|t} \equiv \beta\frac{u'(Y_{t+1})}{u'(Y_t)}$$

and the return is

$$R^j_{t+1} = \frac{V^j_{t+1} + S^j_{t+1}}{S^j_t}$$

2. or, equivalently

$$\boxed{u'(Y_0)S^j_0 = \mathbb{E}_0\left[\sum_{t=1}^{T}\beta^t u'(Y_t)\,V^j_t\right],\ \ j = 1,\ldots,K.}$$

Infinite horizon case, $T = \infty$

- The arbitrage condition is, off course, still valid.

Proposition

Fundamental equilibrium arbitrage condition: if we rule out speculative bubbles, then the price for asset j satisfies

$$S_t^j = \mathbb{E}_t \left[\sum_{\tau=1}^{\infty} \beta^\tau \frac{u'(C_{t+\tau})}{u'(C_t)} V_{t+\tau}^j \right], \quad j = 1, \ldots, K, \quad t \in [0, \infty) \qquad (1)$$

-

Infinite horizon case, $T = \infty$

Proof:

$$
\begin{aligned}
u'(C_t)S_t^j &= \beta \mathbb{E}_t \left[u'(C_{t+1})(S_{t+1}^j + V_{t+1}^j) \right] = \\
&= \lim_{k\to\infty} \beta^k \mathbb{E}_t \left[u'(C_{t+k}) S^j(t+k) \right] + \\
&\quad + \mathbb{E}_t \left[\sum_{\tau=1}^{\infty} \beta^\tau u'(C_{t+\tau}) V^j(t+\tau) \right]
\end{aligned}
$$

If we rule out speculative bubbles, that is

$$
\lim_{k\to\infty} \beta^k \mathbb{E}_t \left[u'(C_{t+k}) S_{t+k}^j \right] = 0
$$

we get equation (1)

Risky and risk-free assets

- For a risky asset

$$\mathbb{E}_t\left[M_{t+1|t}R^j_{t+1}\right] = 1$$

- For a riskless asset with return $R^f_t = 1 + r^f_t$ we have

$$\mathbb{E}_t\left[M_{t+1|t}\right] R^f_{t+1} = 1$$

- Then, for any asset j

$$\mathbb{E}_t\left[M_{t+1|t}R^j_{t+1}\right] = \mathbb{E}_t\left[M_{t+1|t}\right] R^f_{t+1}$$

Equilibrium equity premium: example

Equilibrium risk premium for a Markovian case

- **Assumptions:**
  1. Homogeneous agent finance economy
  2. CRRA Bernoulli utility function
  3. growth factor for the return is Markovian following an iid log-normal distribution
  4. there is one riskless and one risky asset such that the return is Markovian following an iid log-normal distribution
- Problem: **Derive the distribution for the multiplicative risk premium for the risky asset R^j/R^f**
- Solution: the risk premium for asset j, satisfies

$$\boxed{\ln \mathbb{E}_t[R^j_{t+1}] = \ln R^f_{t+1} + \zeta \text{Cov}_t\left[\ln(1+\gamma_{t+1}), \ln R^j_{t+1}\right],\ j = 1, \dots, K}$$

Auxiliary: log-normal distributions

Some properties

Assume two random variables X and Y following log-normal distributions. Then $\ln X$ and $\ln Y$ are normally distrbuted. Then:

$$\ln \mathbb{E}[X] = \mathbb{E}[\ln X] + \frac{1}{2}\mathbb{V}[\ln X]$$

$$\ln \mathbb{E}[\alpha X] = \ln \alpha + \mathbb{E}[\ln X] + \frac{1}{2}\mathbb{V}[\ln X],\ \alpha \text{ constant}$$

$$\ln \mathbb{E}[\alpha X^{\beta}] = \ln \alpha + \beta\mathbb{E}[\ln X] + \frac{\beta^2}{2}\mathbb{V}[\ln X],\ \alpha, \beta,\ \text{constants}$$

$$\ln \mathbb{E}[XY] = \mathbb{E}[\ln X] + \mathbb{E}[\ln Y] + \frac{1}{2}\left\{\mathbb{V}[\ln X] + \mathbb{V}[\ln Y] - 2\,Cov(\ln X, \ln Y)\right\}$$

$$\begin{aligned}\ln \mathbb{E}[X^{\beta} Y] = \beta\mathbb{E}[\ln X] + \mathbb{E}[\ln Y] +& \\ &+ \frac{1}{2}\left\{\beta^2\mathbb{V}[\ln X] + \mathbb{V}[\ln Y] - 2\beta\,Cov(\ln X, \ln Y)\right\}\end{aligned}$$

because $Cov[\beta X, Y] = \beta\, Cov[XY]$.

Equilibrium equity premium example: proof

solution

- The risky asset j follows a iid log-normal distribution: then

$$\ln \mathbb{E}_t[R^j_{t+1}] = \mathbb{E}_t[\ln R^j_{t+1}] + \frac{1}{2}\mathbb{V}_t[\ln R^j_{t+1}]$$

- the endowment process satisfies $Y_{t+1} = (1+\gamma_{t+1})\, Y_t$, where the growth factor follows also a iid log-normal distribution: then

$$\ln \mathbb{E}_t[1+\gamma_{t+1}] = \mathbb{E}_t[\ln(1+\gamma_{t+1})] + \frac{1}{2}\mathbb{V}_t[\ln(1+\gamma_{t+1})]$$

- the utility function is CRRA $u(C) = \frac{C^{1-\zeta}-1}{1-\zeta}$ then the stochastic discount factor is

$$M_{t+1|t} = \beta(1+\gamma_{t+1})^{-\zeta}$$

- then, for any asset, the arbitrage condition holds as

$$1 = \beta\mathbb{E}_t\left[(1+\gamma_{t+1})^{-\zeta} R^j_{t+1}\right]$$

Equilibrium equity premium example: proof

solution (cont.)

- for the riskless asset, after taking logs to the arbitrage condition, we have

$$
\begin{aligned}
0 &= \ln\beta + \ln\mathbb{E}_t\left[(1+\gamma_{t+1})^{-\zeta}R^f_{t+1}\right] \\
&= \ln\beta + \mathbb{E}_t\left[\ln\left((1+\gamma_{t+1})^{-\zeta}R^f_{t+1}\right)\right] + \\
&\quad + \frac{1}{2}\mathbb{V}_t\left[\ln\left((1+\gamma_{t+1})^{-\zeta}R^f_{t+1}\right)\right] \\
&= \ln\beta - \zeta\mathbb{E}_t[\ln(1+\gamma_{t+1})] + \ln R^f_{t+1} + \frac{\zeta^2}{2}\mathbb{V}_t[\ln(1+\gamma_{t+1})]
\end{aligned}
$$

Equilibrium equity premium example: proof

solution (cont.)

- for the risky asset j, after taking logs to the arbitrage condition, we have

$$
\begin{aligned}
0 &= \ln\beta + \ln\mathbb{E}_t\left[(1+\gamma_{t+1})^{-\zeta} R^j_{t+1}\right] = \\
&= \ln\beta - \zeta\mathbb{E}_t[\ln(1+\gamma_{t+1})] + \mathbb{E}_t[\ln R^j_{t+1}] + \\
&\quad + \frac{1}{2}\Big\{\zeta^2\mathbb{V}_t[\ln(1+\gamma_{t+1})] + \mathbb{V}_t[\ln R^j_{t+1}] - \\
&\quad - 2\zeta\mathrm{Cov}_t\left[\ln(1+\gamma_{t+1}), \ln R^j_{t+1}\right]\Big\} = \\
&= -\ln R^f_{t+1} + \mathbb{E}_t[\ln R^j_{t+1}] + \frac{1}{2}\mathbb{V}_t[\ln R^j_{t+1}] - \\
&\quad - \zeta\mathrm{Cov}_t\left[\ln(1+\gamma_{t+1}), \ln R^j_{t+1}\right] = \\
&= -\ln R^f_{t+1} + \ln\mathbb{E}_t\left[R^j_{t+1}\right] - \zeta\mathrm{Cov}_t\left[\ln(1+\gamma_{t+1}), \ln R^j_{t+1}\right].
\end{aligned}
$$

(end of proof)

Equilibrium equity premium

Hansen-Jaganathan bounds

- Let us write the **Equity premium** for asset risky j as: $R^j_{t+1} - R^f_{t+1}$
- Expected premium and standard deviation

$$\mathbb{E}_t\left[R^j_{t+1} - R^f_{t+1}\right],\ \sigma_t\left[R^j_{t+1} - R^f_{t+1}\right]$$

- **Equilibrium equity premium** for risky asset j satisfies, under the assumptions of the model:

$$\mathbb{E}_t\left[M_{t+1|t}\left(R^j_{t+1} - R^f_{t+1}\right)\right] = 0$$

- Then,

$$\boxed{\left|\frac{\mathbb{E}_t\left[R^j_{t+1} - R^f_{t+1}\right]}{\sigma_t\left[R^j_{t+1}\right]}\right| \leq \frac{\sigma_t[M_{t+1|t}]}{\mathbb{E}_t[M_{t+1|t}]}} \qquad (2)$$

the l.h.s is called the Sharpe ratio and r.h.s. the Hansen-Jaganathan bounds

Equilibrium equity premium

Hansen-Jaganathan bounds

- Proof:
- From a standard result on the covariance between two random variables

$$\begin{aligned} & \mathbb{E}_t\left[M_{t+1|t}\left(R^j_{t+1}-R^f_{t+1}\right)\right] = \\ = \; & \mathbb{E}_t\left[M_{t+1|t}\right]\mathbb{E}_t\left[R^j_{t+1}-R^f_{t+1}\right]+\mathrm{Cov}_t\left[M_{t+1|t},\left(R^j_{t+1}-R^f_{t+1}\right)\right] = \\ = \; & 0 \end{aligned}$$

- But

$$\mathrm{Cov}_t\left[M_{t+1|t},\left(R^j_{t+1}-R^f_{t+1}\right)\right] = \rho_{M_{t+1|t},R^j_{t+1}-R^f_{t+1}}\sigma_t(M_{t+1|t})\sigma_t\left(R^j_{t+1}-R^f_{t+1}\right) \quad (3)$$

where $\rho_{M_{t+1|t},R^j_{t+1}-R^f_{t+1}}$ is the correlation coefficient between $M_{t+1|t}$ and $R^j_{t+1}-R^f_{t+1}$

Equilibrium equity premium

Hansen-Jaganathan bounds (cont.)

- Then

$$\frac{\mathbb{E}_t\left[R^j_{t+1} - R^f_{t+1}\right]}{\sigma_t\left[R^j_{t+1}\right]} = \rho_{M_{t+1|t}, R^j_{t+1} - R^f_{t+1}} \frac{\sigma_t[M_{t+1|t}]}{\mathbb{E}_t[M_{t+1|t}]}$$

- We use the fact $|\rho_{M_{t+1|t}, R^j_{t+1} - R^f_{t+1}}| \in [0, 1]$

Equilibrium equity premium

Example

- If we assume that $Y_{t+1} = (1 + \gamma_{t+1})\, Y_t$, the utility function is homogeneous, and $R^f_{t+1} \approx 1/\beta$ then

$$\left| \frac{\mathbb{E}_t \left[R^j_{t+1} - R^f_{t+1} \right]}{\sigma_t \left[R^j_{t+1} \right]} \right| \leq \sigma_t \left[u'(1 + \gamma_{t+1}) \right]$$

- if the utility function is homogeneous, from the equilibrium arbitrage condition

$$\beta \mathbb{E}_t [u'(1 + \gamma_{t+1})] R^f_{t+1} = 1$$

- if $R^f_{t+1} \approx 1/\beta$ then

$$\mathbb{E}_t [u'(1 + \gamma_{t+1})] = 1$$

Equilibrium equity premium: example

- If we ssume a CRRA utility function

$$u(C) = u(C) = \frac{C^{1-\zeta} - 1}{1-\zeta}$$

Then

$$M_{t+1|t} = \beta(1+\gamma_{t+1})^{-\zeta}$$

$$\sigma_t\left[u'(1+\gamma_{t+1})\right] = \sigma_t\left[(1+\gamma_{t+1})^{-\zeta}\right]$$

The higher η the lower $\sigma_t[M_{t+1|t}]$ is.

Equilibrium equity premium puzzle

- **Equity premium puzzle**: if we set $\zeta \approx 2$, we find excessive risk premium in the data:

$$\text{Sharpe ratio} = 0.37 > \frac{\sigma_t[M_{t+1|t})]}{\mathbb{E}_t[M_{t+1|t}]} \approx \frac{0.002}{0.96}$$

- This means that the data displays a higher risk premium than the model would predict (or consumption displays a lower relative volatility than the model predicts)

Equilibrium equity premium puzzle

- This has led to a whole research program (still going on) for macro finance: see `http://academicwebpages.com/preview/mehra/pdf/FIN200201.pdf` for a survey, by introducing in the model:
  - changes in preferences: habit formation, non-additive preferences concerning risk
  - transactions costs, taxes, etc
  - distributions
  - imperfectly competitive environments
- The basic change we have to introduce should do the following: consumption (and investment) should have a smoother behaviour than the model predicts, which means that the reaction of portfolios to changes in asset prices is more rigid, which implies a higher variation in prices to unpredicted shocks.

Non-zero initial wealth

Equilibrium asset pricing: non-zero initial wealth

Assumption assume that the level of initial net wealth is different from zero

Implications:

- we cannot transform the household problem into a household problem for an AD economy
- the household problem becomes a stochastic optimal control problem where financial wealth, A_t, is the state variable and consumption, C_t is the control variable

Equilibrium asset pricing: non-zero initial wealth

Timing and information sequence

- When we introduce the stock of financial wealth A_t, we have to be careful as regards the stock-flow accounting and the exact timing of information should be specified. From now on, we assume the information timing for the end period t, is taken **after** observing C_t and Y_t and **before** observing S_t and $\mathbb{V}_t$.
- That is, in period t:
  1. at the start of period t, between times t and $t+1$ we know the portfolio $\boldsymbol{\theta}_t$ and we observe S^j_{t-1} (set at the end of period $t-1$);
  2. along period t we observe the flow Y_t and we decide over the flow C_t;
  3. close to the time $t+1$, we observe the payoffs V^j_t for $j = 1, \dots, K$ and the asset markets open and draw S^j_t;
  4. we buy a new portfolio θ^j_{t+1} at the market prices S^j_t
  5. And so on.

Equilibrium asset pricing: non-zero initial wealth

Sequential budget constraints

- The stock of asset j at time t is

$$A_t^j = \theta_t^j S_{t-1}^j$$

- and the return of asset j computed at the end of period t is

$$R_t^j = \frac{S_t^j + V_t^j}{S_{t-1}^j} = 1 + r_t^j$$

- Then the period budget constraint for period t is

$$\sum_j R_t^j A_t^j + Y_t = C_t + \sum_j A_{t+1}^j$$

- This is also equivalent to

$$C_t = Y_t + Z_t^\theta$$

Equilibrium asset pricing: non-zero initial wealth

Sequential budget constraints

- The **total** wealth at the beginning of period t is

$$A_t = \sum_{j=1j}^{K} A_t^j$$

- If we define the weight of asset j in total wealth as

$$w_t^j \equiv \frac{A_t^j}{A_t}, \sum_{j=1}^{K} w_t^j = 1$$

then

$$R_t^A A_t - A_{t+1} = (1 + r_t^A) A_t - A_{t+1}$$

where the average return is the rate of return for the whole portfolio

$$R_t^A = \sum_j w_t^j R_t^j, \ r_t^A = \sum_j w_t^j r_t^j,$$

Equilibrium asset pricing: non-zero initial wealth

Sequential budget constraints

- Then the period budget constraint for period t is

$$A_{t+1} = Y_t - C_t + R_t^A A_t,\ t = 0, \ldots, T,$$

- Off course, given $A_t = a_t$ at the beginning of period t (starting a time t and ending at time $t+1$) A_{t+1} is a distribution

$$A_{t+1} = (a_{t+1,1}, \ldots, a_{t+1,N_{t+1|t}})^\top$$

  where $N_{t+1|t}$ is the number of nodes at $t+1$ subsequent to the node s_t at time t;

- We are assuming that all the possible realizations of the budget constraint are of the form:

$$a_{t+1,s_{t+1}|s_t} = y_{t,s_t} - c_{t,s_t} + R^A_{t,s_{t+1}|s_t} a_{t,s_t},\ \text{for } s_t = 1, \ldots, N_t,$$

  and $s_{t+1}|s_t = 1, \ldots, N_{t+1|t}$

Equilibrium asset pricing: non-zero initial wealth

- at time t the household observes A_t
- along period t he gets Y_t and decides on consumption C_t
- at the the end of period he receives a signal R_t^A and decides on the portfolio composition θ_{t+1} such that $A_{t+1} = \sum_{j=1}^{K} \theta_{t+1}^j S_t^j$
- in our case only the savings decision (not the financial decision over $\{\theta_t\}_{t=1}^T$) matters for the determination of the equilibrium stochastic discount factor

Conditional evolution of the asset position

$$\begin{pmatrix} Y_{t,1} - C_{t,1} + R^A_{t,1} \\ \dots \\ Y_{t,N_{t+1|t}} - C_{t,N_{t+1|t}} + R^A_{t,N_{t+1|t}} \end{pmatrix} A_t$$

$$t \qquad\qquad\qquad\qquad t+1$$

$$A_t \qquad\qquad\qquad \begin{pmatrix} A_{t+1,1} \\ \dots \\ A_{t+1,N_{t+1|t}} \end{pmatrix}$$

Equilibrium asset pricing: non-zero initial wealth

The representative agent problem

$$\max_{\{C_t\}_{t=0}^{\infty}} \mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t u(C_t) \right]$$

subject to the **sequence** of random constraints

$$A_{t+1} = Y_t - C_t + R_t^A A_t, \; t = 0, \ldots, T-1$$

given A_0 and the non-Ponzi games condition

$$\lim_{t \to \infty} \mathbb{E}_0 \Big[\prod_{t=1}^{T} R^{-t} A_{t+1} \Big] = 0.$$

Equilibrium asset pricing: non-zero initial wealth

Solving the problem using Dynamic Programming

- We define the value function at time t

$$V(A_t) = \max_{\{C_\tau\}_{\tau=t}^{T}} \mathbb{E}_t \left[\sum_{\tau=t}^{T} \beta^{(\tau-t)} u(C_\tau) \right]$$

- If there is an optimal solution, $\{C_t^*\}_{t=0}^{T}$ for the agent's problem, it satisfies the Hamilton-Jacobi-Bellman (HJB) equation

$$V(A_t) = \max_{C_t} \{ u(C_t) + \beta \mathbb{E}_t [V(A_{t+1})] \}$$

Solving the household-investor problem using DP

- Assume there is only one asset: $K = 1$.
- In order to solve the problem:
  1. we derive the first order conditions, for an optimal consumption,
  $$u'(C_t) = \beta \mathbb{E}_t \left[V'(A_{t+1}) \right]$$
  because $A_{t+1} = Y_t - C_t + R_t A_t$ and $\partial A_{t+1} / \partial C_t = -1$
  2. and we use the envelope condition (taking the derivative to A_t)
  $$V'(A_t) = \beta \, \mathbb{E}_t \left[V'(A_{t+1}) R_t \right]$$

Equilibrium asset pricing: non-zero initial wealth

- **Optimality condition for the household**: again

$$u'(C_t) = \mathbb{E}_t\left[u'(C_{t+1})R_{t+1}\right]$$

- Proof: using the law of iterated expectations, the envelopment theorem and the measurability properties of the variables, we have

$$\begin{aligned}
u'(C_t) &= \beta\,\mathbb{E}_t\left[V'(A_{t+1})\right] \\
&= \beta\,\mathbb{E}_t\left[\beta\,\mathbb{E}_{t+1}\left[V'(A_{t+2})R_{t+1}\right]\right] \\
&= \beta\,\mathbb{E}_t\left[\beta\,\mathbb{E}_{t+1}\left[V'(A_{t+2})\right]\,R_{t+1}\right] \\
&= \beta\,\mathbb{E}_t\left[u'(C_{t+1})\,R_{t+1}\right]
\end{aligned}$$

- Now, for any number of assets. $K > 1$
- The first order conditions for an optimal consumption is the same

$$u'(C_t) = \beta \mathbb{E}_t \left[V'(A_{t+1}) \right]$$

- but we have $A_t = A_t^1 + \ldots + A_t^K$ and $R_t^A A_t = R_t^1 A_t^1 + \ldots + R_t^K A_t^K$
- applying the envelope condition for any asset j

$$V'(A_t) \frac{\partial A_t}{\partial A_t^j} = \beta \mathbb{E}_t \left[V'(A_{t+1}) \frac{\partial A_{t+1}}{\partial A_t^j} \right], \; j = 1, \ldots, K$$

- we get

$$V'(A_t) = \beta \mathbb{E}_t \left[V'(A_{t+1}) R_t^j \right], \; j = 1, \ldots, K$$

- Then the arbitrage condition for the household choice of asset j is

$$u'(C_t) = \beta \mathbb{E}_t \left[u'(C_{t+1}) R^j_{t+1} \right], \; j = 1, \ldots, K$$

- or, equivalently

$$u'(C_t) S^j_t = \beta \mathbb{E}_t \left[u'(C_{t+1}) (V^j_{t+1} + S^j_{t+1}) \right], \; j = 1, \ldots, K, \; t = 0, \ldots, T$$

Using stochastic optimal control

- We obtain a similar result using the stochastic Pontriyagin's principle
- Define the hamiltonian, for period f

$$H_t = u(C_t) + \Lambda_t \left(Y_t - C_t + R_t\, A_t \right)$$

  where $\{\Lambda_t\}_{t=0}^{\infty}$ is an adapted $\mathcal{F}_t$ process, but λ_t is conditional on the information at period t

- The optimality condition is, conditional on the information at t

$$\frac{\partial h_t}{\partial c_t} = 0 \iff u'(c_t) = \lambda_t$$

- The Euler equation is

$$\lambda_t = \beta\, \mathbb{E}_t\Big[\frac{\partial H_{t+1}}{\partial C_{t+1}}\Big] = \beta\, \mathbb{E}_t\Big[\Lambda_{t+1}\, R_{t+1}\Big]$$

- Then

$$u'(C_t) = \beta\, \mathbb{E}_t\Big[u'(C_{t+1})\, R_{t+1}\Big]$$