Remarks

- When interest rates are stochastic, forward and futures prices are no longer theoretically identical.
  - Suppose interest rates are uncertain and futures prices move in the same direction as interest rates.
  - Then futures prices will exceed forward prices.
- For short-term contracts, the differences tend to be small.
- Unless stated otherwise, assume forward and futures prices are identical.

Futures Options

- The underlying of a futures option is a futures contract.
- Upon exercise, the option holder takes a position in the futures contract with a futures price equal to the option's strike price.
  - A call holder acquires a long futures position.
  - A put holder acquires a short futures position.
- The futures contract is then marked to market.
- And the futures position of the two parties will be at the prevailing futures price.

Futures Options (concluded)

- It works as if the call holder received a futures contract for the strike price X minus the prevailing futures price F_t.
  - This futures contract has zero value.
- It works as if the put holder sold a futures contract for the strike price X minus the prevailing futures price F_t.

Forward Options

- Similar to futures options except that what is delivered is a forward contract with a delivery price equal to the option's strike price.
  - Exercising a call forward option results in a long position in a forward contract.
  - Exercising a put forward option results in a short position in a forward contract.
- Exercising a forward option incurs no immediate cash flows.

Example

- Consider a call with strike \$100 and an expiration date in September.
- The underlying asset is a forward contract with a delivery date in December.
- Suppose the forward price in July is \$110.
- Upon exercise, the call holder receives a forward contract with a delivery price of \$100.
- If an offsetting position is then taken in the forward market, a \$10 profit in December will be assured.
- A call on the futures would realize the \$10 profit in July.

Some Pricing Relations

- Let delivery take place at time T, the current time be 0, and the option on the futures or forward contract have expiration date t $(t \leq T)$.
- Assume a constant, positive interest rate.
- Although forward price equals futures price, a forward option does not have the same value as a futures option.
- The payoffs of calls at time t are

$$\begin{aligned} \text{futures option} &= \max(F_t - X, 0), & (36) \\ \text{forward option} &= \max(F_t - X, 0)\, e^{-r(T-t)}. & (37) \end{aligned}$$

Some Pricing Relations (concluded)

- A European futures option is worth the same as the corresponding European option on the underlying asset if the futures contract has the same maturity as the options.
  - Futures price equals spot price at maturity.
  - This conclusion is independent of the model for the spot price.

Put-Call Parity

The put-call parity is slightly different from the one in Eq. (18) on p. 181.

Theorem 11 *(1) For European options on futures contracts,* $C = P - (X - F)\, e^{-rt}$*. (2) For European options on forward contracts,* $C = P - (X - F)\, e^{-rT}$*.*

- See text for proof.

Early Exercise and Forward Options

The early exercise feature is not valuable.

Theorem 12 *American forward options should not be exercised before expiration as long as the probability of their ending up out of the money is positive.*

- See text for proof.

Early exercise may be optimal for American futures options even if the underlying asset generates no payouts.

Theorem 13 *American futures options may be exercised optimally before expiration.*

Black Model[a]

- Formulas for European futures options:

$$\begin{aligned} C &= Fe^{-rt} N(x) - Xe^{-rt} N(x - \sigma\sqrt{t}), \quad (38) \\ P &= Xe^{-rt} N(-x + \sigma\sqrt{t}) - Fe^{-rt} N(-x), \end{aligned}$$

where $x \equiv \frac{\ln(F/X) + (\sigma^2/2)\, t}{\sigma\sqrt{t}}$.

- Formulas (38) are related to those for options on a stock paying a continuous dividend yield.
- In fact, they are exactly Eqs. (24) on p. 261 with the dividend yield q set to the interest rate r and the stock price S replaced by the futures price F.

[a] Black (1976).

Black Model (concluded)

- This observation incidentally proves Theorem 13 (p. 393).
- For European forward options, just multiply the above formulas by $e^{-r(T-t)}$.
  - Forward options differ from futures options by a factor of $e^{-r(T-t)}$ based on Eqs. (36)–(37) on p. 390.

Binomial Model for Forward and Futures Options

- Futures price behaves like a stock paying a continuous dividend yield of r.
  - The futures price at time 0 is (p. 370)
  $$F = Se^{rT}.$$
  - From Lemma 7 (p. 242), the expected value of S at time Δt in a risk-neutral economy is
  $$Se^{r\Delta t}.$$
  - So the expected futures price at time Δt is
  $$Se^{r\Delta t}e^{r(T-\Delta t)} = Se^{rT} = F.$$

Binomial Model for Forward and Futures Options (concluded)

- Under the BOPM, the risk-neutral probability for the futures price is

$$p_{\mathrm{f}} \equiv (1-d)/(u-d)$$

by Eq. (25) on p. 263.

  - The futures price moves from F to Fu with probability p_{f} and to Fd with probability $1-p_{\mathrm{f}}$.

- The binomial tree algorithm for forward options is identical except that Eq. (37) on p. 390 is the payoff.

Spot and Futures Prices under BOPM

- The futures price is related to the spot price via $F = Se^{rT}$ if the underlying asset pays no dividends.
- The stock price moves from $S = Fe^{-rT}$ to
$$Fue^{-r(T-\Delta t)} = Sue^{r\Delta t}$$
with probability p_{f} per period.
- The stock price moves from $S = Fe^{-rT}$ to
$$Sde^{r\Delta t}$$
with probability $1 - p_{\mathrm{f}}$ per period.

Negative Probabilities Revisited

- As $0 < p_{\mathrm{f}} < 1$, we have $0 < 1 - p_{\mathrm{f}} < 1$ as well.
- The problem of negative risk-neutral probabilities is now solved:
  - Suppose the stock pays a continuous dividend yield of q.
  - Build the tree for the futures price F of the futures contract expiring at the same time as the option.
  - Calculate S from F at each node via $S = Fe^{-(r-q)(T-t)}$.
- Of course, this model may not be suitable for pricing barrier options (why?).

Swaps

- Swaps are agreements between two counterparties to exchange cash flows in the future according to a predetermined formula.
- There are two basic types of swaps: interest rate and currency.
- An interest rate swap occurs when two parties exchange interest payments periodically.
- Currency swaps are agreements to deliver one currency against another (our focus here).

Currency Swaps

- A currency swap involves two parties to exchange cash flows in different currencies.
- Consider the following fixed rates available to party A and party B in U.S. dollars and Japanese yen:

	Dollars	Yen
A	$D_{\mathrm{A}}\%$	$Y_{\mathrm{A}}\%$
B	$D_{\mathrm{B}}\%$	$Y_{\mathrm{B}}\%$

- Suppose A wants to take out a fixed-rate loan in yen, and B wants to take out a fixed-rate loan in dollars.

Currency Swaps (continued)

- A straightforward scenario is for A to borrow yen at $Y_{\mathrm{A}}\%$ and B to borrow dollars at $D_{\mathrm{B}}\%$.
- But suppose A is *relatively* more competitive in the dollar market than the yen market, and vice versa for B.
  - That is, $Y_{\mathrm{B}} - Y_{\mathrm{A}} < D_{\mathrm{B}} - D_{\mathrm{A}}$.
- Consider this alternative arrangement:
  - A borrows dollars.
  - B borrows yen.
  - They enter into a currency swap with a bank as the intermediary.

Currency Swaps (concluded)

- The counterparties exchange principal at the beginning and the end of the life of the swap.
- This act transforms A's loan into a yen loan and B's yen loan into a dollar loan.
- The total gain is $((D_{\mathrm{B}} - D_{\mathrm{A}}) - (Y_{\mathrm{B}} - Y_{\mathrm{A}}))\%$:
  - The total interest rate is originally $(Y_{\mathrm{A}} + D_{\mathrm{B}})\%$.
  - The new arrangement has a smaller total rate of $(D_{\mathrm{A}} + Y_{\mathrm{B}})\%$.
- Transactions will happen only if the gain is distributed so that the cost to each party is less than the original.

Example

- A and B face the following borrowing rates:

	Dollars	Yen
A	9%	10%
B	12%	11%

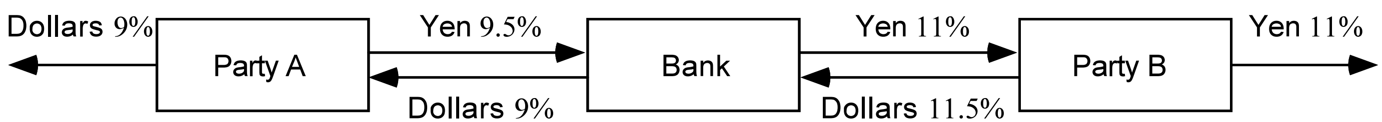
- A wants to borrow yen, and B wants to borrow dollars.
- A can borrow yen directly at 10%.
- B can borrow dollars directly at 12%.

Example (continued)

- The rate differential in dollars (3%) is different from that in yen (1%).
- So a currency swap with a total saving of $3 - 1 = 2\%$ is possible.
- A is relatively more competitive in the dollar market.
- B is relatively more competitive in the the yen market.

Example (concluded)

- Figure next page shows an arrangement which is beneficial to all parties involved.
  - A effectively borrows yen at 9.5%.
  - B borrows dollars at 11.5%.
  - The gain is 0.5% for A, 0.5% for B, and, if we treat dollars and yen identically, 1% for the bank.


Dollars 9%
Party A
Yen 9.5%
Dollars 9%
Bank
Yen 11%
Dollars 11.5%
Party B
Yen 11%

As a Package of Cash Market Instruments

- Assume no default risk.
- Take B on p. 407 as an example.
- The swap is equivalent to a long position in a yen bond paying 11% annual interest and a short position in a dollar bond paying 11.5% annual interest.
- The pricing formula is $SP_{\text{Y}} - P_{\text{D}}$.
  - P_{D} is the dollar bond's value in dollars.
  - P_{Y} is the yen bond's value in yen.
  - S is the \$/yen spot exchange rate.

As a Package of Cash Market Instruments (concluded)

- The value of a currency swap depends on:
  - The term structures of interest rates in the currencies involved.
  - The spot exchange rate.
- It has zero value when

$$SP_{\mathrm{Y}} = P_{\mathrm{D}}.$$

Example

- Take a two-year swap on p. 407 with principal amounts of US$1 million and 100 million yen.
- The payments are made once a year.
- The spot exchange rate is 90 yen/$ and the term structures are flat in both nations—8% in the U.S. and 9% in Japan.
- For B, the value of the swap is (in millions of USD)

$$\begin{aligned} & \frac{1}{90} \times \left(11 \times e^{-0.09} + 11 \times e^{-0.09 \times 2} + 111 \times e^{-0.09 \times 3}\right) \\ - & \left(0.115 \times e^{-0.08} + 0.115 \times e^{-0.08 \times 2} + 1.115 \times e^{-0.08 \times 3}\right) \quad = \quad 0.074. \end{aligned}$$

As a Package of Forward Contracts

- From Eq. (33) on p. 376, the forward contract maturing i years from now has a dollar value of

$$f_i \equiv (SY_i)\, e^{-qi} - D_i e^{-ri}. \tag{39}$$

  - Y_i is the yen inflow at year i.
  - S is the \$/yen spot exchange rate.
  - q is the yen interest rate.
  - D_i is the dollar outflow at year i.
  - r is the dollar interest rate.

As a Package of Forward Contracts (concluded)

- For simplicity, flat term structures were assumed.
- Generalization is straightforward.

Example

- Take the swap in the example on p. 410.
- Every year, B receives 11 million yen and pays 0.115 million dollars.
- In addition, at the end of the third year, B receives 100 million yen and pays 1 million dollars.
- Each of these transactions represents a forward contract.
- $Y_1 = Y_2 = 11$, $Y_3 = 111$, $S = 1/90$, $D_1 = D_2 = 0.115$, $D_3 = 1.115$, $q = 0.09$, and $r = 0.08$.
- Plug in these numbers to get $f_1 + f_2 + f_3 = 0.074$ million dollars as before.

Stochastic Processes and Brownian Motion

Of all the intellectual hurdles which the human mind
has confronted and has overcome in the last
fifteen hundred years, the one which seems to me
to have been the most amazing in character and
the most stupendous in the scope of its
consequences is the one relating to
the problem of motion.
— Herbert Butterfield (1900–1979)

Stochastic Processes

- A stochastic process
$$X = \{ X(t) \}$$
is a time series of random variables.
- $X(t)$ (or X_t) is a random variable for each time t and is usually called the state of the process at time t.
- A realization of X is called a sample path.
- A sample path defines an ordinary function of t.

Stochastic Processes (concluded)

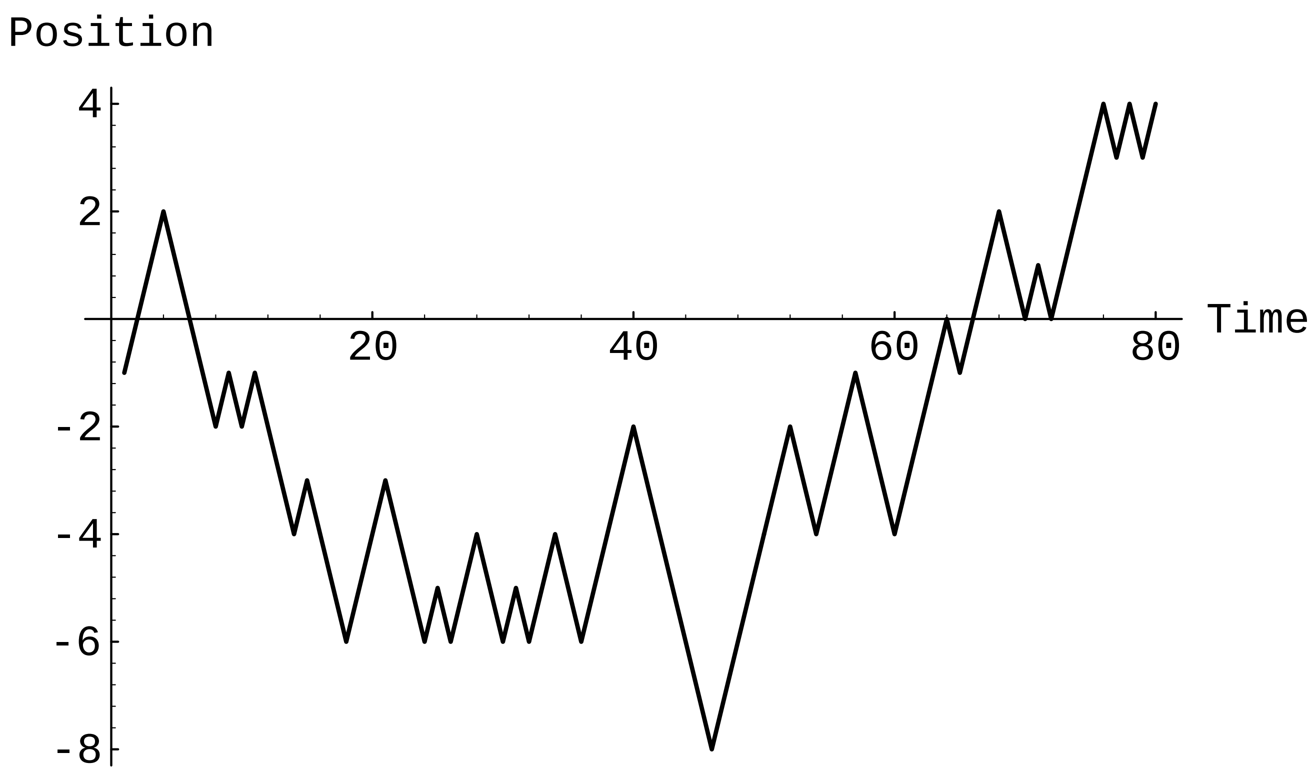
- If the times t form a countable set, X is called a discrete-time stochastic process or a time series.
- In this case, subscripts rather than parentheses are usually employed, as in

$$X = \{ X_n \}.$$

- If the times form a continuum, X is called a continuous-time stochastic process.

Random Walks

- The binomial model is a random walk in disguise.
- Consider a particle on the integer line, $0, \pm 1, \pm 2, \ldots$.
- In each time step, it can make one move to the right with probability p or one move to the left with probability $1 - p$.
  - This random walk is symmetric when $p = 1/2$.
- Connection with the BOPM: The particle's position denotes the cumulative number of up moves minus that of down moves.


Position
4
2
-2
-4
-6
-8
20
40
60
80
Time

Random Walk with Drift

$$X_n = \mu + X_{n-1} + \xi_n.$$

- ξ_n are independent and identically distributed with zero mean.
- Drift μ is the expected change per period.
- Note that this process is continuous in space.

Martingales[a]

- $\{ X(t), t \geq 0 \}$ is a martingale if $E[\,|\,X(t)\,|\,] < \infty$ for $t \geq 0$ and

$$E[\, X(t) \,|\, X(u), 0 \leq u \leq s \,] = X(s), \quad s \leq t. \tag{40}$$

- In the discrete-time setting, a martingale means

$$E[\, X_{n+1} \,|\, X_1, X_2, \ldots, X_n \,] = X_n. \tag{41}$$

- X_n can be interpreted as a gambler's fortune after the nth gamble.
- Identity (41) then says the expected fortune after the $(n+1)$th gamble equals the fortune after the nth gamble regardless of what may have occurred before.

[a] The origin of the name is somewhat obscure.

Martingales (concluded)

- A martingale is therefore a notion of fair games.
- Apply the law of iterated conditional expectations to both sides of Eq. (41) on p. 421 to yield

$$E[\,X_n\,] = E[\,X_1\,] \tag{42}$$

for all n.

- Similarly, $E[\,X(t)\,] = E[\,X(0)\,]$ in the continuous-time case.

Still a Martingale?

- Suppose we replace Eq. (41) on p. 421 with

$$E[\, X_{n+1} \,|\, X_n \,] = X_n.$$

- It also says past history cannot affect the future.
- But is it equivalent to the original definition (41) on p. 421?[a]

[a]Contributed by Mr. Hsieh, Chicheng (M9007304) on April 13, 2005.

Still a Martingale? (continued)

- Well, no.[a]
- Consider this random walk with drift:

$$X_i = \begin{cases} X_{i-1} + \xi_i, & \text{if } i \text{ is even,} \\ X_{i-2}, & \text{otherwise.} \end{cases}$$

- Above, ξ_n are random variables with zero mean.

[a]Contributed by Mr. Zhang, Ann-Sheng (B89201033) on April 13, 2005.

Still a Martingale? (concluded)

- It is not hard to see that

$$E[\, X_i \,|\, X_{i-1} \,] = \begin{cases} X_{i-1}, & \text{if } i \text{ is even,} \\ X_{i-1}, & \text{otherwise.} \end{cases}$$

  - It is a martingale by the "new" definition.

- But

$$E[\, X_i \,|\, \ldots, X_{i-2}, X_{i-1} \,] = \begin{cases} X_{i-1}, & \text{if } i \text{ is even,} \\ X_{i-2}, & \text{otherwise.} \end{cases}$$

  - It is not a martingale by the original definition.

Example

- Consider the stochastic process

$$\{ Z_n \equiv \sum_{i=1}^{n} X_i, n \geq 1 \},$$

where X_i are independent random variables with zero mean.

- This process is a martingale because

$$\begin{aligned}
& E[\, Z_{n+1} \,|\, Z_1, Z_2, \ldots, Z_n \,] \\
= \;& E[\, Z_n + X_{n+1} \,|\, Z_1, Z_2, \ldots, Z_n \,] \\
= \;& E[\, Z_n \,|\, Z_1, Z_2, \ldots, Z_n \,] + E[\, X_{n+1} \,|\, Z_1, Z_2, \ldots, Z_n \,] \\
= \;& Z_n + E[\, X_{n+1} \,] = Z_n.
\end{aligned}$$

Probability Measure

- A martingale is defined with respect to a probability measure, under which the expectation is taken.
  - A probability measure assigns probabilities to states of the world.
- A martingale is also defined with respect to an information set.
  - In the characterizations (40)–(41) on p. 421, the information set contains the current and past values of X by default.
  - But it needs not be so.

Probability Measure (continued)

- A stochastic process $\{ X(t), t \geq 0 \}$ is a martingale with respect to information sets $\{ I_t \}$ if, for all $t \geq 0$, $E[\,|\,X(t)\,|\,] < \infty$ and

$$E[\, X(u) \,|\, I_t \,] = X(t)$$

for all $u > t$.

- The discrete-time version: For all $n > 0$,

$$E[\, X_{n+1} \,|\, I_n \,] = X_n,$$

given the information sets $\{ I_n \}$.

Probability Measure (concluded)

- The above implies $E[\,X_{n+m}\,|\,I_n\,] = X_n$ for any $m > 0$ by Eq. (15) on p. 139.
  - A typical I_n is the price information up to time n.
  - Then the above identity says the FVs of X will not deviate systematically from today's value given the price history.

Example

- Consider the stochastic process $\{ Z_n - n\mu, n \geq 1 \}$.
  - $Z_n \equiv \sum_{i=1}^{n} X_i$.
  - $X_1, X_2, \ldots$ are independent random variables with mean μ.
- Now,

$$
\begin{aligned}
& E[\, Z_{n+1} - (n+1)\,\mu \,|\, X_1, X_2, \ldots, X_n \,] \\
= \;& E[\, Z_{n+1} \,|\, X_1, X_2, \ldots, X_n \,] - (n+1)\,\mu \\
= \;& E[\, Z_n + X_{n+1} \,|\, X_1, X_2, \ldots, X_n \,] - (n+1)\,\mu \\
= \;& Z_n + \mu - (n+1)\,\mu \\
= \;& Z_n - n\mu.
\end{aligned}
$$

Example (concluded)

- Define

$$I_n \equiv \{ X_1, X_2, \ldots, X_n \}.$$

- Then

$$\{ Z_n - n\mu, n \geq 1 \}$$

is a martingale with respect to $\{ I_n \}$.

Martingale Pricing

- Recall that the price of a European option is the expected discounted future payoff at expiration in a risk-neutral economy.
- This principle can be generalized using the concept of martingale.
- Recall the recursive valuation of European option via

$$C = [\, pC_u + (1-p)\, C_d \,]/R.$$

  - p is the risk-neutral probability.
  - \$1 grows to \$$R$ in a period.

Martingale Pricing (continued)

- Let $C(i)$ denote the value of the option at time i.
- Consider the discount process

$$\left\{ \frac{C(i)}{R^i}, i = 0, 1, \ldots, n \right\}.$$

- Then,

$$E\left[\left. \frac{C(i+1)}{R^{i+1}} \,\right|\, C(i) = C \right] = \frac{pC_u + (1-p)\,C_d}{R^{i+1}} = \frac{C}{R^i}.$$

Martingale Pricing (continued)

- It is easy to show that

$$E\left[\frac{C(k)}{R^k} \,\middle|\, C(i) = C \right] = \frac{C}{R^i}, \quad i \leq k. \tag{43}$$

- This formulation assumes:[a]

1. The model is Markovian: The distribution of the future is determined by the present (time i) and not the past.
2. The payoff depends only on the terminal price of the underlying asset (Asian options do not qualify).

[a]Contributed by Mr. Wang, Liang-Kai (Ph.D. student, ECE, University of Wisconsin-Madison) and Mr. Hsiao, Huan-Wen (B90902081) on May 3, 2006.

Martingale Pricing (continued)

- In general, the discount process is a martingale in that

$$E_i^{\pi}\left[\frac{C(k)}{R^k}\right] = \frac{C(i)}{R^i}, \quad i \leq k. \tag{44}$$

  - E_i^{π} is taken under the risk-neutral probability conditional on the price information up to time i.

- This risk-neutral probability is also called the EMM, or the equivalent martingale (probability) measure.

Martingale Pricing (continued)

- Equation (44) holds for all assets, not just options.
- When interest rates are stochastic, the equation becomes

$$\frac{C(i)}{M(i)} = E_i^{\pi}\left[\frac{C(k)}{M(k)}\right], \quad i \leq k. \tag{45}$$

  - $M(j)$ is the balance in the money market account at time j using the rollover strategy with an initial investment of \$1.
  - So it is called the bank account process.
- It says the discount process is a martingale under π.

Martingale Pricing (continued)

- If interest rates are stochastic, then $M(j)$ is a random variable.
  - $M(0) = 1$.
  - $M(j)$ is known at time $j - 1$.
- Identity (45) on p. 436 is the general formulation of risk-neutral valuation.

Martingale Pricing (concluded)

Theorem 14 *A discrete-time model is arbitrage-free if and only if there exists a probability measure such that the discount process is a martingale. This probability measure is called the risk-neutral probability measure.*

Futures Price under the BOPM

- Futures prices form a martingale under the risk-neutral probability.
  - The expected futures price in the next period is
$$p_{\mathrm{f}} F u + (1 - p_{\mathrm{f}})\, F d = F \left(\frac{1-d}{u-d}\, u + \frac{u-1}{u-d}\, d \right) = F$$
    (p. 396).
- Can be generalized to
$$F_i = E_i^{\pi}[\, F_k \,], \quad i \le k,$$
  where F_i is the futures price at time i.
- It holds under stochastic interest rates, too.

Martingale Pricing and Numeraire

- The martingale pricing formula (45) on p. 436 uses the money market account as numeraire.[a]
  - It expresses the price of any asset *relative to* the money market account.
- The money market account is not the only choice for numeraire.
- Suppose asset S's value is positive at all times.

[a]Leon Walras (1834–1910).

Martingale Pricing and Numeraire (concluded)

- Choose S as numeraire.
- Martingale pricing says there exists a risk-neutral probability π under which the relative price of any asset C is a martingale:

$$\frac{C(i)}{S(i)} = E_i^{\pi}\left[\frac{C(k)}{S(k)}\right], \quad i \leq k.$$

  - $S(j)$ denotes the price of S at time j.
- So the discount process remains a martingale.

Example

- Take the binomial model with two assets.
- In a period, asset one's price can go from S to S_1 or S_2.
- In a period, asset two's price can go from P to P_1 or P_2.
- Assume
$$\frac{S_1}{P_1} < \frac{S}{P} < \frac{S_2}{P_2}$$
to rule out arbitrage opportunities.

Example (continued)

- For any derivative security, let C_1 be its price at time one if asset one's price moves to S_1.
- Let C_2 be its price at time one if asset one's price moves to S_2.
- Replicate the derivative by solving

$$\begin{aligned} \alpha S_1 + \beta P_1 &= C_1, \\ \alpha S_2 + \beta P_2 &= C_2, \end{aligned}$$

using α units of asset one and β units of asset two.

Example (continued)

- This yields

$$\alpha = \frac{P_2 C_1 - P_1 C_2}{P_2 S_1 - P_1 S_2} \quad \text{and} \quad \beta = \frac{S_2 C_1 - S_1 C_2}{S_2 P_1 - S_1 P_2}.$$

- The derivative costs

$$\begin{aligned} C &= \alpha S + \beta P \\ &= \frac{P_2 S - P S_2}{P_2 S_1 - P_1 S_2} C_1 + \frac{P S_1 - P_1 S}{P_2 S_1 - P_1 S_2} C_2. \end{aligned}$$

Example (concluded)

- It is easy to verify that

$$\frac{C}{P} = p\,\frac{C_1}{P_1} + (1-p)\,\frac{C_2}{P_2}.$$

  – Above,

$$p \equiv \frac{(S/P) - (S_2/P_2)}{(S_1/P_1) - (S_2/P_2)}.$$

- The derivative's price using asset two as numeraire (i.e., C/P) is a martingale under the risk-neutral probability p.
- The expected returns of the two assets are irrelevant.

Brownian Motion[a]

- Brownian motion is a stochastic process $\{ X(t), t \geq 0 \}$ with the following properties.

  1. $X(0) = 0$, unless stated otherwise.

  2. for any $0 \leq t_0 < t_1 < \cdots < t_n$, the random variables
$$X(t_k) - X(t_{k-1})$$
  for $1 \leq k \leq n$ are independent.[b]

  3. for $0 \leq s < t$, $X(t) - X(s)$ is normally distributed with mean $\mu(t-s)$ and variance $\sigma^2(t-s)$, where μ and $\sigma \neq 0$ are real numbers.

---

[a] Robert Brown (1773–1858).

[b] So $X(t) - X(s)$ is independent of $X(r)$ for $r \leq s < t$.

Brownian Motion (concluded)

- Such a process will be called a (μ, σ) Brownian motion with drift μ and variance σ^2.
- The existence and uniqueness of such a process is guaranteed by Wiener's theorem.[a]
- Although Brownian motion is a continuous function of t with probability one, it is almost nowhere differentiable.
- The $(0, 1)$ Brownian motion is also called the Wiener process.

[a]Norbert Wiener (1894–1964).

Example

- If $\{ X(t), t \geq 0 \}$ is the Wiener process, then $X(t) - X(s) \sim N(0, t-s)$.
- A (μ, σ) Brownian motion $Y = \{ Y(t), t \geq 0 \}$ can be expressed in terms of the Wiener process:

$$Y(t) = \mu t + \sigma X(t). \tag{46}$$

- Note that $Y(t+s) - Y(t) \sim N(\mu s, \sigma^2 s)$.

Brownian Motion as Limit of Random Walk

Claim 1 *A* (μ, σ) *Brownian motion is the limiting case of random walk.*

- A particle moves Δx to the left with probability $1 - p$.
- It moves to the right with probability p after Δt time.
- Assume $n \equiv t/\Delta t$ is an integer.
- Its position at time t is

$$Y(t) \equiv \Delta x \left(X_1 + X_2 + \cdots + X_n \right).$$

Brownian Motion as Limit of Random Walk (continued)

- (continued)
  - Here

$$X_i \equiv \begin{cases} +1 & \text{if the } i\text{th move is to the right,} \\ -1 & \text{if the } i\text{th move is to the left.} \end{cases}$$

  - X_i are independent with $\text{Prob}[\, X_i = 1\,] = p = 1 - \text{Prob}[\, X_i = -1\,]$.
- Recall $E[\, X_i\,] = 2p - 1$ and $\text{Var}[\, X_i\,] = 1 - (2p-1)^2$.

Brownian Motion as Limit of Random Walk (continued)

- Therefore,

$$E[\,Y(t)\,] = n(\Delta x)(2p-1),$$

$$\mathrm{Var}[\,Y(t)\,] = n(\Delta x)^2 \left[\,1-(2p-1)^2\,\right].$$

- With $\Delta x \equiv \sigma\sqrt{\Delta t}$ and $p \equiv [\,1+(\mu/\sigma)\sqrt{\Delta t}\,]/2$,

$$\begin{aligned} E[\,Y(t)\,] &= n\sigma\sqrt{\Delta t}\,(\mu/\sigma)\sqrt{\Delta t} = \mu t, \\ \mathrm{Var}[\,Y(t)\,] &= n\sigma^2\Delta t\left[\,1-(\mu/\sigma)^2\Delta t\,\right] \to \sigma^2 t, \end{aligned}$$

as $\Delta t \to 0$.

Brownian Motion as Limit of Random Walk (concluded)

- Thus, $\{ Y(t), t \geq 0 \}$ converges to a (μ, σ) Brownian motion by the central limit theorem.
- Brownian motion with zero drift is the limiting case of symmetric random walk by choosing $\mu = 0$.
- Note that

$$\begin{aligned} & \mathrm{Var}[\, Y(t + \Delta t) - Y(t) \,] \\ = & \mathrm{Var}[\, \Delta x \, X_{n+1} \,] = (\Delta x)^2 \times \mathrm{Var}[\, X_{n+1} \,] \to \sigma^2 \Delta t. \end{aligned}$$

- Similarity to the the BOPM: The p is identical to the probability in Eq. (23) on p. 239 and $\Delta x = \ln u$.

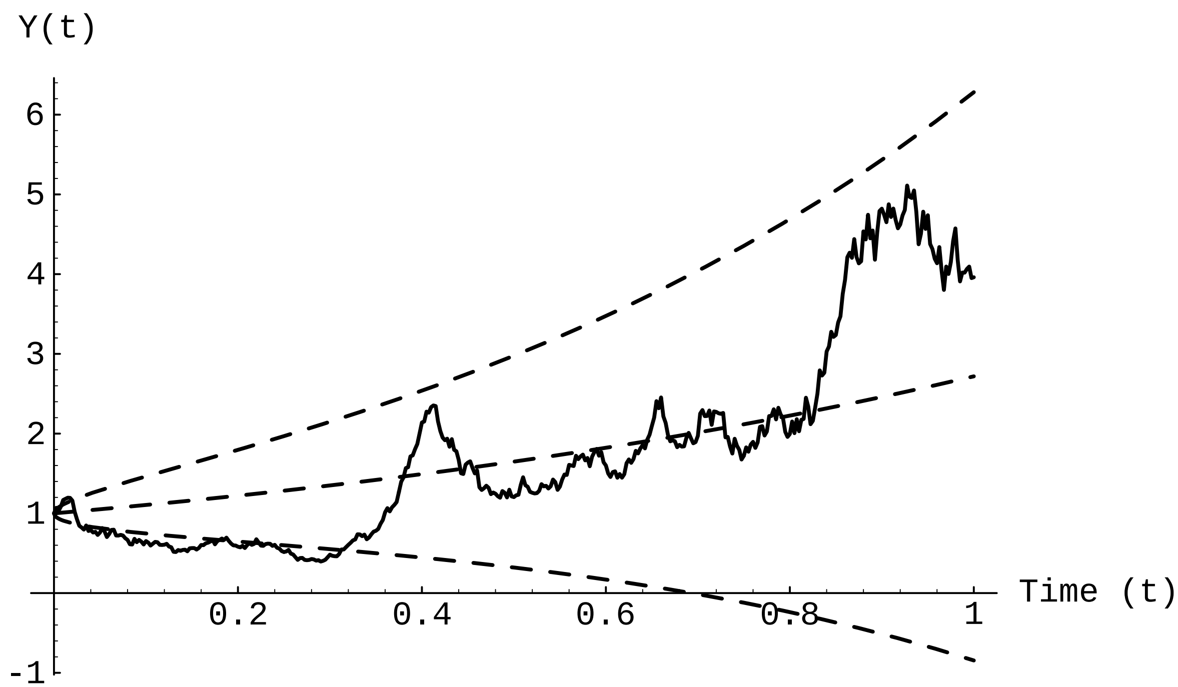
Geometric Brownian Motion

- Let $X \equiv \{ X(t), t \geq 0 \}$ be a Brownian motion process.
- The process
$$\{ Y(t) \equiv e^{X(t)}, t \geq 0 \},$$
is called geometric Brownian motion.
- Suppose further that X is a (μ, σ) Brownian motion.
- $X(t) \sim N(\mu t, \sigma^2 t)$ with moment generating function
$$E\left[e^{sX(t)} \right] = E\left[Y(t)^s \right] = e^{\mu ts + (\sigma^2 ts^2/2)}$$
from Eq. (16) on p 141.

Geometric Brownian Motion (continued)

- In particular,

$$
\begin{aligned}
E[\,Y(t)\,] &= e^{\mu t+(\sigma^2 t/2)},\\
\mathrm{Var}[\,Y(t)\,] &= E\left[\,Y(t)^2\,\right] - E[\,Y(t)\,]^2\\
&= e^{2\mu t+\sigma^2 t}\left(e^{\sigma^2 t}-1\right).
\end{aligned}
$$


Y(t)
6
5
4
3
2
1
-1
0.2
0.4
0.6
0.8
1
Time (t)

Geometric Brownian Motion (continued)

- It is useful for situations in which percentage changes are independent and identically distributed.
- Let Y_n denote the stock price at time n and $Y_0 = 1$.
- Assume relative returns

$$X_i \equiv \frac{Y_i}{Y_{i-1}}$$

are independent and identically distributed.

Geometric Brownian Motion (concluded)

- Then
$$\ln Y_n = \sum_{i=1}^{n} \ln X_i$$
is a sum of independent, identically distributed random variables.
- Thus $\{ \ln Y_n, n \geq 0 \}$ is approximately Brownian motion.
  - And $\{ Y_n, n \geq 0 \}$ is approximately geometric Brownian motion.