Equilibrium Term Structure Models

8. What's your problem? Any moron can understand bond pricing models.

— *Top Ten Lies Finance Professors Tell Their Students*

Introduction

- We now survey equilibrium models.
- Recall that the spot rates satisfy

$$r(t,T) = -\frac{\ln P(t,T)}{T-t}$$

by Eq. (129) on p. 1005.

- Hence the discount function $P(t,T)$ suffices to establish the spot rate curve.
- All models to follow are short rate models.
- Unless stated otherwise, the processes are risk-neutral.

The Vasicek Model[a]

- The short rate follows

$$dr = \beta(\mu - r)\,dt + \sigma\,dW.$$

- The short rate is pulled to the long-term mean level μ at rate β.
- Superimposed on this "pull" is a normally distributed stochastic term $\sigma\,dW$.
- Since the process is an Ornstein-Uhlenbeck process,

$$E[\,r(T)\,|\,r(t) = r\,] = \mu + (r - \mu)\,e^{-\beta(T-t)}$$

from Eq. (78) on p. 585.

[a] Vasicek (1977). Vasicek co-founded KMV, which was sold to Moody's for USD$210 million in 2002.

The Vasicek Model (continued)

- The price of a zero-coupon bond paying one dollar at maturity can be shown to be

$$P(t,T) = A(t,T)\, e^{-B(t,T)\, r(t)}, \tag{142}$$

where

$$A(t,T) = \begin{cases} \exp\left[\frac{(B(t,T)-T+t)(\beta^2\mu-\sigma^2/2)}{\beta^2} - \frac{\sigma^2 B(t,T)^2}{4\beta} \right] & \text{if } \beta \neq 0, \\ \exp\left[\frac{\sigma^2 (T-t)^3}{6} \right] & \text{if } \beta = 0. \end{cases}$$

and

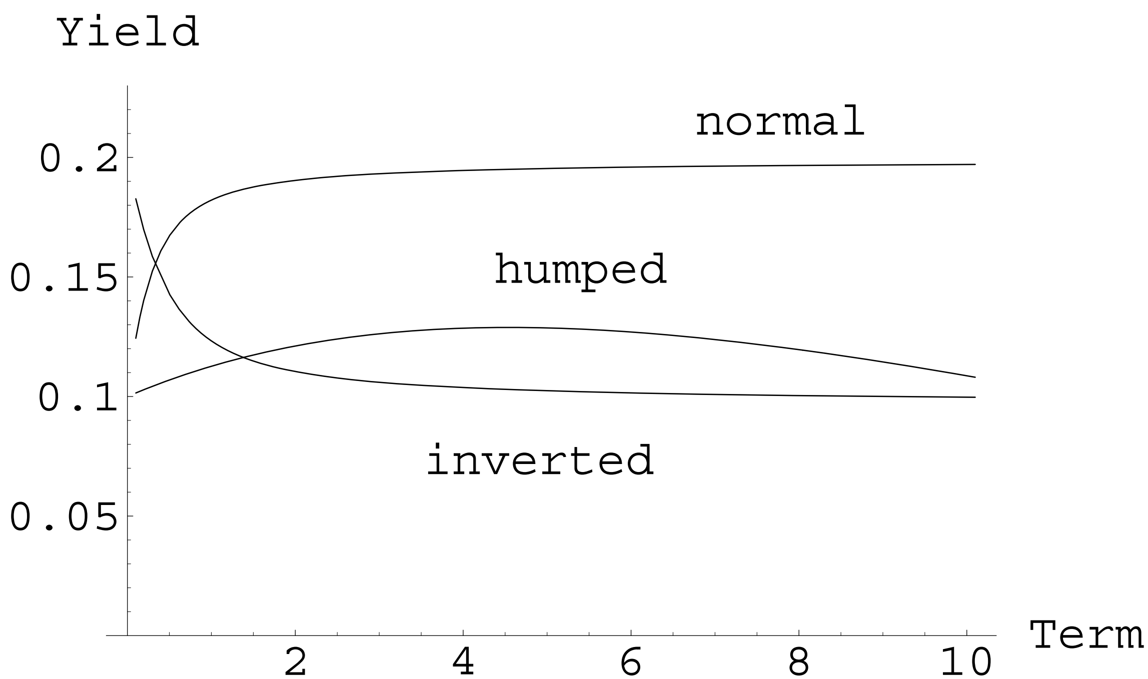
$$B(t,T) = \begin{cases} \frac{1-e^{-\beta(T-t)}}{\beta} & \text{if } \beta \neq 0, \\ T-t & \text{if } \beta = 0. \end{cases}$$

The Vasicek Model (concluded)

- If $\beta = 0$, then P goes to infinity as $T \to \infty$.
- Sensibly, P goes to zero as $T \to \infty$ if $\beta \neq 0$.
- Even if $\beta \neq 0$, P may exceed one for a finite T.
- The spot rate volatility structure is the curve

$$(\partial r(t,T)/\partial r)\,\sigma = \sigma B(t,T)/(T-t).$$

- When $\beta > 0$, the curve tends to decline with maturity.
- The speed of mean reversion, β, controls the shape of the curve.
- Indeed, higher β leads to greater attenuation of volatility with maturity.


Yield
normal
0.2
0.15
humped
0.1
inverted
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2
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10

The Vasicek Model: Options on Zeros[a]

- Consider a European call with strike price X expiring at time T on a zero-coupon bond with par value \$1 and maturing at time $s > T$.
- Its price is given by

$$P(t,s)\,N(x) - X P(t,T)\,N(x - \sigma_v).$$

[a] Jamshidian (1989).

The Vasicek Model: Options on Zeros (concluded)

- Above

$$
\begin{aligned}
x &\stackrel{\Delta}{=} \frac{1}{\sigma_v} \ln\left(\frac{P(t,s)}{P(t,T)\,X}\right) + \frac{\sigma_v}{2}, \\
\sigma_v &\equiv v(t,T)\,B(T,s), \\
v(t,T)^2 &\stackrel{\Delta}{=} \begin{cases} \frac{\sigma^2\left[1-e^{-2\beta(T-t)}\right]}{2\beta}, & \text{if } \beta \neq 0 \\ \sigma^2(T-t), & \text{if } \beta = 0 \end{cases}.
\end{aligned}
$$

- By the put-call parity, the price of a European put is

$$
XP(t,T)\,N(-x+\sigma_v) - P(t,s)\,N(-x).
$$

Binomial Vasicek

- Consider a binomial model for the short rate in the time interval $[\,0, T\,]$ divided into n identical pieces.
- Let $\Delta t \stackrel{\Delta}{=} T/n$ and

$$p(r) \stackrel{\Delta}{=} \frac{1}{2} + \frac{\beta(\mu - r)\sqrt{\Delta t}}{2\sigma}.$$

- The following binomial model converges to the Vasicek model,[a]

$$r(k+1) = r(k) + \sigma\sqrt{\Delta t}\;\xi(k), \quad 0 \leq k < n.$$

[a]Nelson & Ramaswamy (1990).

Binomial Vasicek (continued)

- Above, $\xi(k) = \pm 1$ with

$$\text{Prob}[\,\xi(k) = 1\,] = \begin{cases} p(r(k)), & \text{if } 0 \leq p(r(k)) \leq 1 \\ 0, & \text{if } p(r(k)) < 0, \\ 1, & \text{if } 1 < p(r(k)). \end{cases}$$

- Observe that the probability of an up move, p, is a decreasing function of the interest rate r.
- This is consistent with mean reversion.

Binomial Vasicek (concluded)

- The rate is the same whether it is the result of an up move followed by a down move or a down move followed by an up move.
- The binomial tree combines.
- The key feature of the model that makes it happen is its *constant* volatility, σ.

The Cox-Ingersoll-Ross Model[a]

- It is the following square-root short rate model:

$$dr = \beta(\mu - r)\,dt + \sigma\sqrt{r}\,dW. \tag{143}$$

- The diffusion differs from the Vasicek model by a multiplicative factor $\sqrt{r}$.
- The parameter β determines the speed of adjustment.
- The short rate can reach zero only if $2\beta\mu < \sigma^2$.
- See text for the bond pricing formula.

[a] Cox, Ingersoll, & Ross (1985).

Binomial CIR

- We want to approximate the short rate process in the time interval $[\,0, T\,]$.
- Divide it into n periods of duration $\Delta t \stackrel{\Delta}{=} T/n$.
- Assume $\mu, \beta \geq 0$.
- A direct discretization of the process is problematic because the resulting binomial tree will *not* combine.

Binomial CIR (continued)

- Instead, consider the transformed process

$$x(r) \stackrel{\Delta}{=} 2\sqrt{r}/\sigma.$$

- By Ito's lemma (p. 562),

$$dx = m(x)\, dt + dW,$$

where

$$m(x) \stackrel{\Delta}{=} 2\beta\mu/(\sigma^2 x) - (\beta x/2) - 1/(2x).$$

- This new process has a constant volatility.
- Thus its binomial tree combines.

Binomial CIR (continued)

- Construct the combining tree for r as follows.
- First, construct a tree for x.
- Then transform each node of the tree into one for r via the inverse transformation
$$r = f(x) \triangleq \frac{x^2 \sigma^2}{4}$$
(see p. 1054).
- But when $x \approx 0$ (so $r \approx 0$), the moments may not be matched well.[a]

[a]Nawalkha & Beliaeva (2007).

$$
\begin{array}{ccccc}
 & & & & x + 2\sqrt{\Delta t} \\
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 & \nearrow & & \searrow & \\
x & & & & x \\
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 & & x - \sqrt{\Delta t} & & \\
 & & & \searrow & \\
 & & & & x - 2\sqrt{\Delta t}
\end{array}
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\begin{array}{ccccc}
 & & & & f(x + 2\sqrt{\Delta t}) \\
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 & \nearrow & & \searrow & \\
f(x) & & & & f(x) \\
 & \searrow & & \nearrow & \\
 & & f(x - \sqrt{\Delta t}) & & \\
 & & & \searrow & \\
 & & & & f(x - 2\sqrt{\Delta t})
\end{array}
$$

Binomial CIR (continued)

- The probability of an up move at each node r is

$$p(r) \stackrel{\Delta}{=} \frac{\beta(\mu - r)\,\Delta t + r - r^-}{r^+ - r^-}.$$

  - $r^+ \stackrel{\Delta}{=} f(x + \sqrt{\Delta t})$ denotes the result of an up move from r.
  - $r^- \stackrel{\Delta}{=} f(x - \sqrt{\Delta t})$ the result of a down move.

- Finally, set the probability $p(r)$ to one as r goes to zero to make the probability stay between zero and one.

Binomial CIR (concluded)

- It can be shown that

$$p(r) = \left(\beta\mu - \frac{\sigma^2}{4} \right) \sqrt{\frac{\Delta t}{r}} - B\sqrt{r\Delta t} + C,$$

  for some $B \geq 0$ and $C > 0$.[a]

- If $\beta\mu - (\sigma^2/4) \geq 0$, the up-move probability $p(r)$ decreases if and only if short rate r increases.

- Even if $\beta\mu - (\sigma^2/4) < 0$, $p(r)$ tends to decrease as r increases and decrease as r declines.

- This phenomenon agrees with mean reversion.

[a]Thanks to a lively class discussion on May 28, 2014.

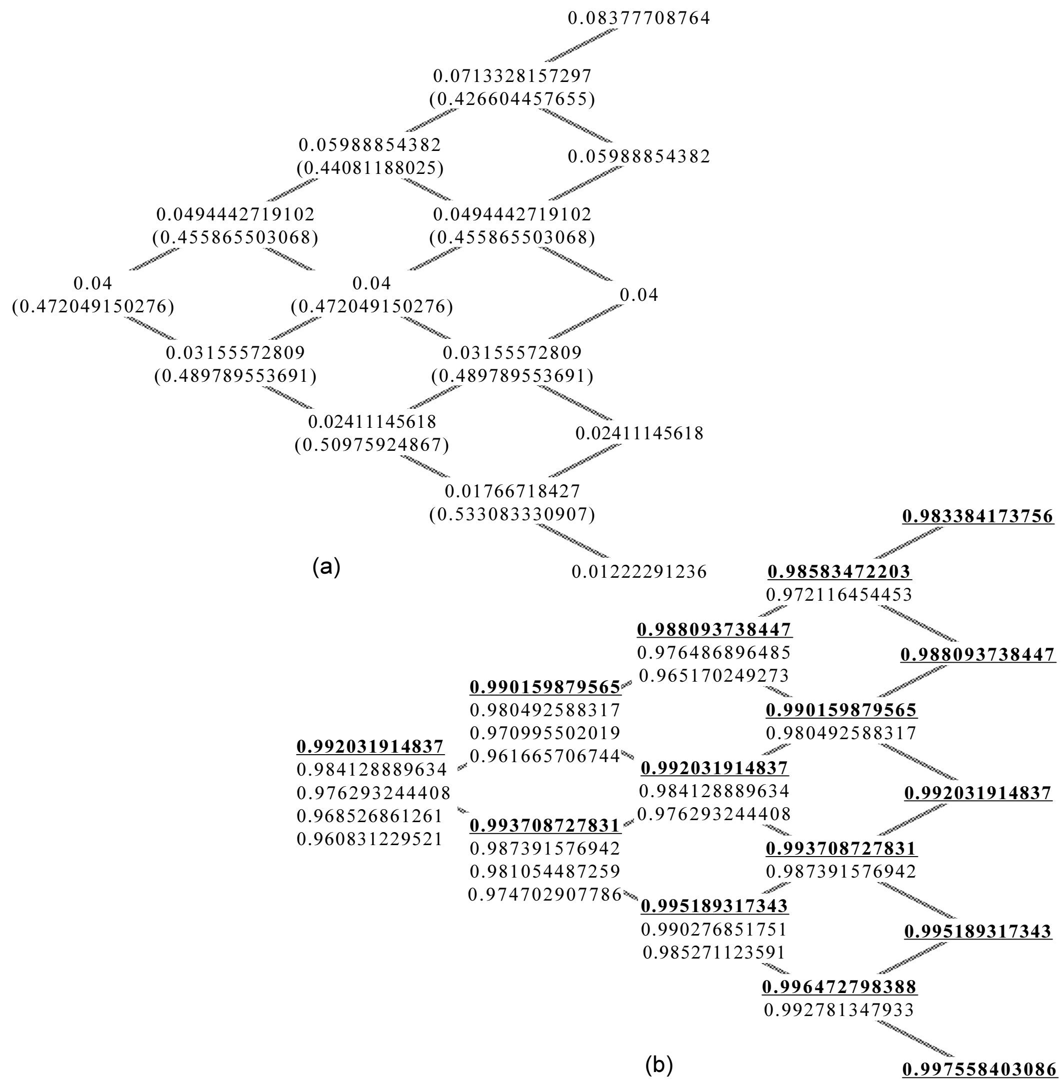
Numerical Examples

- Consider the process,

$$0.2\,(0.04 - r)\,dt + 0.1\sqrt{r}\,dW,$$

  for the time interval $[\,0, 1\,]$ given the initial rate $r(0) = 0.04$.

- We shall use $\Delta t = 0.2$ (year) for the binomial approximation.
- See p. 1058(a) for the resulting binomial short rate tree with the up-move probabilities in parentheses.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0.960831229521
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0.987391576942
0.981054487259
0.974702907786
0.993708727831
0.987391576942
0.995189317343
0.990276851751
0.985271123591
0.995189317343
0.996472798388
0.992781347933
0.997558403086
(b)

Numerical Examples (concluded)

- Consider the node which is the result of an up move from the root.
- Since the root has $x = 2\sqrt{r(0)}/\sigma = 4$, this particular node's x value equals $4 + \sqrt{\Delta t} = 4.4472135955$.
- Use the inverse transformation to obtain the short rate

$$\frac{x^2 \times (0.1)^2}{4} \approx 0.0494442719102.$$

- Once the short rates are in place, computing the probabilities is easy.
- Convergence is quite good (see p. 369 of the textbook).

A General Method for Constructing Binomial Models[a]

- We are given a continuous-time process,

$$dy = \alpha(y,t)\,dt + \sigma(y,t)\,dW.$$

- Need to make sure the binomial model's drift and diffusion converge to the above process.
- Set the probability of an up move to

$$\frac{\alpha(y,t)\,\Delta t + y - y_{\mathrm{d}}}{y_{\mathrm{u}} - y_{\mathrm{d}}}.$$

- Here $y_{\mathrm{u}} \stackrel{\Delta}{=} y + \sigma(y,t)\sqrt{\Delta t}$ and $y_{\mathrm{d}} \stackrel{\Delta}{=} y - \sigma(y,t)\sqrt{\Delta t}$ represent the two rates that follow the current rate y.

[a]Nelson & Ramaswamy (1990).

A General Method (continued)

- The displacements are identical, at $\sigma(y,t)\sqrt{\Delta t}$.
- But the binomial tree may not combine as

$$\begin{aligned} & \sigma(y,t)\sqrt{\Delta t} - \sigma(y_{\mathrm{u}}, t+\Delta t)\sqrt{\Delta t} \\ \neq \quad & -\sigma(y,t)\sqrt{\Delta t} + \sigma(y_{\mathrm{d}}, t+\Delta t)\sqrt{\Delta t} \end{aligned}$$

  in general.
- When $\sigma(y,t)$ is a constant independent of y, equality holds and the tree combines.

A General Method (continued)

- To achieve this, define the transformation

$$x(y, t) \stackrel{\Delta}{=} \int^{y} \sigma(z, t)^{-1} \, dz.$$

- Then x follows

$$dx = m(y, t) \, dt + dW$$

for some $m(y, t)$.[a]

- The diffusion term is now a constant, and the binomial tree for x combines.

[a] See Exercise 25.2.13 of the textbook.

A General Method (concluded)

- The transformation is unique.[a]
- The probability of an up move remains

$$\frac{\alpha(y(x,t),t)\,\Delta t + y(x,t) - y_{\mathrm{d}}(x,t)}{y_{\mathrm{u}}(x,t) - y_{\mathrm{d}}(x,t)},$$

  where $y(x,t)$ is the inverse transformation of $x(y,t)$ from x back to y.

- Note that

$$\begin{aligned} y_{\mathrm{u}}(x,t) &\stackrel{\Delta}{=} y(x+\sqrt{\Delta t}, t+\Delta t), \\ y_{\mathrm{d}}(x,t) &\stackrel{\Delta}{=} y(x-\sqrt{\Delta t}, t+\Delta t). \end{aligned}$$

[a] Chiu (`R98723059`) (2012).

Examples

- The transformation is

$$\int^{r} (\sigma\sqrt{z})^{-1}\, dz = \frac{2\sqrt{r}}{\sigma}$$

  for the CIR model.

- The transformation is

$$\int^{S} (\sigma z)^{-1}\, dz = \frac{\ln S}{\sigma}$$

  for the Black-Scholes model.

- The familiar BOPM and CRR in fact discretize $\ln S$ not S.

On One-Factor Short Rate Models

- By using only the short rate, they ignore other rates on the yield curve.
- Such models also restrict the volatility to be a function of interest rate *levels* only.
- The prices of all bonds move in the same direction at the same time (their magnitudes may differ).
- The returns on all bonds thus become highly correlated.
- In reality, there seems to be a certain amount of independence between short- and long-term rates.

On One-Factor Short Rate Models (continued)

- One-factor models therefore cannot accommodate nondegenerate correlation structures across maturities.
- Derivatives whose values depend on the correlation structure will be mispriced.
- The calibrated models may not generate term structures as concave as the data suggest.
- The term structure empirically changes in slope and curvature as well as makes parallel moves.
- This is inconsistent with the restriction that all segments of the term structure be perfectly correlated.

On One-Factor Short Rate Models (concluded)

- Multi-factor models lead to families of yield curves that can take a greater variety of shapes and can better represent reality.
- But they are much harder to think about and work with.
- They also take much more computer time—the curse of dimensionality.
- These practical concerns limit the use of multifactor models to two- or three-factor ones.

Options on Coupon Bonds[a]

- Assume the market discount function P is a monotonically decreasing function of the short rate r.
  - Such as a one-factor short rate model.
- The price of a European option on a coupon bond can be calculated from those on zero-coupon bonds.
- Consider a European call expiring at time T on a bond with par value \$1.
- Let X denote the strike price.

[a] Jamshidian (1989).

Options on Coupon Bonds (continued)

- The bond has cash flows $c_1, c_2, \ldots, c_n$ at times $t_1, t_2, \ldots, t_n$, where $t_i > T$ for all i.
- The payoff for the option is

$$\max\left\{\left[\sum_{i=1}^{n} c_i P(r(T), T, t_i)\right] - X, 0\right\}.$$

- At time T, there is a unique value r^* for $r(T)$ that renders the coupon bond's price equal the strike price X.

Options on Coupon Bonds (continued)

- This r^* can be obtained by solving

$$X = \sum_{i=1}^{n} c_i P(r, T, t_i)$$

numerically for r.

- Let

$$X_i \stackrel{\Delta}{=} P(r^*, T, t_i),$$

the value at time T of a zero-coupon bond with par value \$1 and maturing at time t_i if $r(T) = r^*$.

- Note that $P(r, T, t_i) \geq X_i$ if and only if $r \leq r^*$.

Options on Coupon Bonds (concluded)

- As $X = \sum_i c_i X_i$, the option's payoff equals

$$\max\left\{ \left[\sum_{i=1}^{n} c_i P(r(T), T, t_i) \right] - \left[\sum_{i=1}^{n} c_i X_i \right], 0 \right\}$$

$$= \sum_{i=1}^{n} c_i \times \max(P(r(T), T, t_i) - X_i, 0).$$

- Thus the call is a package of n options on the underlying zero-coupon bond.
- Why can't we do the same thing for Asian options?[a]

[a]Contributed by Mr. Yang, Jui-Chung (`D97723002`) on May 20, 2009.

No-Arbitrage Term Structure Models

How much of the structure of our theories
really tells us about things in nature,
and how much do we contribute ourselves?
— Arthur Eddington (1882–1944)

Motivations

- Recall the difficulties facing equilibrium models mentioned earlier.
  - They usually require the estimation of the market price of risk.
  - They cannot fit the market term structure.
  - But consistency with the market is often mandatory in practice.

No-Arbitrage Models[a]

- No-arbitrage models utilize the full information of the term structure.
- They accept the observed term structure as consistent with an unobserved and unspecified equilibrium.
- From there, arbitrage-free movements of interest rates or bond prices over time are modeled.
- By definition, the market price of risk must be reflected in the current term structure; hence the resulting interest rate process is risk-neutral.

[a] Ho & Lee (1986). Thomas Lee is a "billionaire founder" of Thomas H. Lee Partners LP, according to *Bloomberg* on May 26, 2012.

No-Arbitrage Models (concluded)

- No-arbitrage models can specify the dynamics of zero-coupon bond prices, forward rates, or the short rate.
- Bond price and forward rate models are usually non-Markovian (path dependent).
- In contrast, short rate models are generally constructed to be explicitly Markovian (path independent).
- Markovian models are easier to handle computationally.

The Ho-Lee Model[a]

- The short rates at any given time are evenly spaced.
- Let p denote the risk-neutral probability that the short rate makes an up move.
- We shall adopt continuous compounding.

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[a]Ho & Lee (1986).

$$
\begin{array}{cccccc}
 & & & & & \nearrow \\
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 & & r_2 & & & \\
 & \nearrow & & \searrow & & \nearrow \\
r_1 & & & & r_3 + v_3 & \\
 & \searrow & & \nearrow & & \searrow \\
 & & r_2 + v_2 & & & \\
 & & & \searrow & & \nearrow \\
 & & & & r_3 + 2v_3 & \\
 & & & & & \searrow
\end{array}
$$

The Ho-Lee Model (continued)

- The Ho-Lee model starts with zero-coupon bond prices $P(t, t+1), P(t, t+2), \ldots$ at time t identified with the root of the tree.
- Let the discount factors in the next period be

$$
\begin{array}{ll}
P_{\mathrm{d}}(t+1, t+2), P_{\mathrm{d}}(t+1, t+3), \ldots, & \text{if short rate moves down,} \\
P_{\mathrm{u}}(t+1, t+2), P_{\mathrm{u}}(t+1, t+3), \ldots, & \text{if short rate moves up.}
\end{array}
$$

- By backward induction, it is not hard to see that for $n \geq 2$,

$$
P_{\mathrm{u}}(t+1, t+n) = P_{\mathrm{d}}(t+1, t+n)\, e^{-(v_2 + \cdots + v_n)} \tag{144}
$$

(see p. 376 of the textbook).

The Ho-Lee Model (continued)

- It is also not hard to check that the n-period zero-coupon bond has yields

$$
\begin{aligned}
y_{\mathrm{d}}(n) &\stackrel{\Delta}{=} -\frac{\ln P_{\mathrm{d}}(t+1,t+n)}{n-1} \\
y_{\mathrm{u}}(n) &\stackrel{\Delta}{=} -\frac{\ln P_{\mathrm{u}}(t+1,t+n)}{n-1} = y_{\mathrm{d}}(n) + \frac{v_2 + \cdots + v_n}{n-1}
\end{aligned}
$$

- The volatility of the yield to maturity for this bond is therefore

$$
\begin{aligned}
\kappa_n &\stackrel{\Delta}{=} \sqrt{p y_{\mathrm{u}}(n)^2 + (1-p)\, y_{\mathrm{d}}(n)^2 - [\, p y_{\mathrm{u}}(n) + (1-p)\, y_{\mathrm{d}}(n)\,]^2} \\
&= \sqrt{p(1-p)}\; (y_{\mathrm{u}}(n) - y_{\mathrm{d}}(n)) \\
&= \sqrt{p(1-p)}\; \frac{v_2 + \cdots + v_n}{n-1}.
\end{aligned}
$$

The Ho-Lee Model (concluded)

- In particular, the short rate volatility is determined by taking $n = 2$:

$$\sigma = \sqrt{p(1-p)}\, v_2. \tag{145}$$

- The variance of the short rate therefore equals

$$p(1-p)(r_{\mathrm{u}} - r_{\mathrm{d}})^2,$$

where r_{u} and r_{d} are the two successor rates.[a]

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[a]Contrast this with the lognormal model (122) on p. 946.

The Ho-Lee Model: Volatility Term Structure

- The volatility term structure is composed of

$$\kappa_2, \kappa_3, \ldots .$$

  - It is independent of

$$r_2, r_3, \ldots .$$

- It is easy to compute the v_is from the volatility structure, and vice versa (review p. 1080).
- The r_is can be computed by forward induction.
- The volatility structure is supplied by the market.

The Ho-Lee Model: Bond Price Process

- In a risk-neutral economy, the initial discount factors satisfy

$$P(t, t{+}n) = [\, p P_{\mathrm{u}}(t{+}1, t{+}n) + (1{-}p)\, P_{\mathrm{d}}(t{+}1, t{+}n) \,]\, P(t, t{+}1).$$

- Combine the above with Eq. (144) on p. 1079 and assume $p = 1/2$ to obtain[a]

$$P_{\mathrm{d}}(t+1, t+n) = \frac{P(t, t+n)}{P(t, t+1)} \, \frac{2 \times \exp[\, v_2 + \cdots + v_n \,]}{1 + \exp[\, v_2 + \cdots + v_n \,]},$$

$$P_{\mathrm{u}}(t+1, t+n) = \frac{P(t, t+n)}{P(t, t+1)} \, \frac{2}{1 + \exp[\, v_2 + \cdots + v_n \,]}.$$

[a] In the limit, only the volatility matters; the first formula is similar to multiple logistic regression.

The Ho-Lee Model: Bond Price Process (concluded)

- The bond price tree combines.[a]
- Suppose all v_i equal some constant v and $\delta \stackrel{\Delta}{=} e^v > 0$.
- Then

$$\begin{aligned} P_{\mathrm{d}}(t+1, t+n) &= \frac{P(t, t+n)}{P(t, t+1)} \frac{2\delta^{n-1}}{1+\delta^{n-1}}, \\ P_{\mathrm{u}}(t+1, t+n) &= \frac{P(t, t+n)}{P(t, t+1)} \frac{2}{1+\delta^{n-1}}. \end{aligned}$$

- Short rate volatility $\sigma = v/2$ by Eq. (145) on p. 1081.
- Price derivatives by taking expectations under the risk-neutral probability.

[a]See Exercise 26.2.3 of the textbook.

Calibration

- The Ho-Lee model can be calibrated in $O(n^2)$ time using state prices.
- But it can actually be calibrated in $O(n)$ time.
  - Derive the v_i's in linear time.
  - Derive the r_i's in linear time.[a]

[a] See Programming Assignment 26.2.6 of the textbook.

The Ho-Lee Model: Yields and Their Covariances

- The one-period rate of return of an n-period zero-coupon bond is

$$r(t, t+n) \stackrel{\Delta}{=} \ln \left(\frac{P(t+1, t+n)}{P(t, t+n)} \right).$$

- Its two possible value are

$$\ln \frac{P_{\mathrm{d}}(t+1, t+n)}{P(t, t+n)} \quad \text{and} \quad \ln \frac{P_{\mathrm{u}}(t+1, t+n)}{P(t, t+n)}.$$

- Thus the variance of return is

$$\mathrm{Var}[\, r(t, t+n)\,] = p(1-p)((n-1)\, v)^2 = (n-1)^2 \sigma^2.$$

The Ho-Lee Model: Yields and Their Covariances (concluded)

- The covariance between $r(t, t+n)$ and $r(t, t+m)$ is[a]

$$(n-1)(m-1)\,\sigma^2.$$

- As a result, the correlation between any two one-period rates of return is one.
- Strong correlation between rates is inherent in all one-factor Markovian models.

[a]See Exercise 26.2.7 of the textbook.

The Ho-Lee Model: Short Rate Process

- The continuous-time limit of the Ho-Lee model is[a]

$$dr = \theta(t)\, dt + \sigma\, dW.$$

- This is Vasicek's model with the mean-reverting drift replaced by a deterministic, time-dependent drift.
- A nonflat term structure of volatilities can be achieved if the short rate volatility is also made time varying,

$$dr = \theta(t)\, dt + \sigma(t)\, dW.$$

- This corresponds to the discrete-time model in which v_i are not all identical.

[a] See Exercise 26.2.10 of the textbook.

The Ho-Lee Model: Some Problems

- Future (nominal) interest rates may be negative.
- The short rate volatility is independent of the rate level.

Problems with No-Arbitrage Models in General

- Interest rate movements should reflect shifts in the model's state variables (factors) not its parameters.
- Model *parameters*, such as the drift $\theta(t)$ in the continuous-time Ho-Lee model, should be stable over time.
- But in practice, no-arbitrage models capture yield curve shifts through the recalibration of parameters.
  - A new model is thus born everyday.

Problems with No-Arbitrage Models in General (concluded)

- This in effect says the model estimated at some time does not describe the term structure of interest rates and their volatilities at other times.
- Consequently, a model's intertemporal behavior is suspect, and using it for hedging and risk management may be unreliable.

The Black-Derman-Toy Model[a]

- This model is extensively used by practitioners.
- The BDT short rate process is the lognormal binomial interest rate process described on pp. 942ff.[b]
- The volatility structure is given by the market.
- From it, the short rate volatilities (thus v_i) are determined together with r_i.

---

[a] Black, Derman, & Toy (BDT) (1990), but essentially finished in 1986 according to Mehrling (2005).

[b] Repeated on next page.

$$
\begin{tikzcd}
 & & & r_4 \\
 & & r_3 \arrow[ur] \arrow[dr] & \\
 & r_2 \arrow[ur] \arrow[dr] & & r_4 v_4 \\
r_1 \arrow[ur] \arrow[dr] & & r_3 v_3 \arrow[ur] \arrow[dr] & \\
 & r_2 v_2 \arrow[ur] \arrow[dr] & & r_4 v_4^2 \\
 & & r_3 v_3^2 \arrow[ur] \arrow[dr] & \\
 & & & r_4 v_4^3
\end{tikzcd}
$$

The Black-Derman-Toy Model (concluded)

- Our earlier binomial interest rate tree, in contrast, assumes v_i are given a priori.
- Lognormal models preclude negative short rates.

The BDT Model: Volatility Structure

- The volatility structure defines the yield volatilities of zero-coupon bonds of various maturities.
- Let the yield volatility of the i-period zero-coupon bond be denoted by κ_i.
- P_{u} is the price of the i-period zero-coupon bond one period from now if the short rate makes an up move.
- P_{d} is the price of the i-period zero-coupon bond one period from now if the short rate makes a down move.

The BDT Model: Volatility Structure (concluded)

- Corresponding to these two prices are the following yields to maturity,

$$\begin{aligned} y_{\mathrm{u}} &\stackrel{\Delta}{=} P_{\mathrm{u}}^{-1/(i-1)} - 1, \\ y_{\mathrm{d}} &\stackrel{\Delta}{=} P_{\mathrm{d}}^{-1/(i-1)} - 1. \end{aligned}$$

- The yield volatility is defined as

$$\kappa_i \stackrel{\Delta}{=} \frac{\ln(y_{\mathrm{u}}/y_{\mathrm{d}})}{2}$$

(recall Eq. (128) on p. 992).

The BDT Model: Calibration

- The inputs to the BDT model are riskless zero-coupon bond yields and their volatilities.
- For economy of expression, all numbers are period based.
- Suppose inductively that we have calculated

$$(r_1, v_1), (r_2, v_2), \ldots, (r_{i-1}, v_{i-1}).$$

  - They define the binomial tree up to period $i-1$.
- We now proceed to calculate r_i and v_i to extend the tree to period i.

The BDT Model: Calibration (continued)

- Assume the price of the i-period zero can move to P_{u} or P_{d} one period from now.
- Let y denote the current i-period spot rate, which is known.
- In a risk-neutral economy,
$$\frac{P_{\mathrm{u}} + P_{\mathrm{d}}}{2(1 + r_1)} = \frac{1}{(1 + y)^i}. \tag{146}$$
- Obviously, P_{u} and P_{d} are functions of the unknown r_i and v_i.

The BDT Model: Calibration (continued)

- Viewed from now, the future $(i-1)$-period spot rate at time 1 is uncertain.
- Recall that y_{u} and y_{d} represent the spot rates at the up node and the down node, respectively (p. 1096).
- With κ_i^2 denoting their variance, we have

$$\kappa_i = \frac{1}{2} \ln \left(\frac{{P_{\mathrm{u}}}^{-1/(i-1)} - 1}{{P_{\mathrm{d}}}^{-1/(i-1)} - 1} \right). \tag{147}$$

- Solving Eqs. (146)–(147) for r and v with backward induction takes $O(i^2)$ time.
  - That leads to a cubic-time algorithm.

The BDT Model: Calibration (continued)

- We next employ forward induction to derive a quadratic-time calibration algorithm.[a]
- Recall that forward induction inductively figures out, by moving *forward* in time, how much \$1 at a node contributes to the price.[b]
- This number is called the state price and is the price of the claim that pays \$1 at that node and zero elsewhere.

---

[a] W. J. Chen (`R84526007`) & Lyuu (1997); Lyuu (1999).

[b] Review p. 969(a).

The BDT Model: Calibration (continued)

- Let the unknown baseline rate for period i be $r_i = r$.
- Let the unknown multiplicative ratio be $v_i = v$.
- Let the state prices at time $i-1$ be
$$P_1, P_2, \ldots, P_i.$$
- They correspond to rates
$$r, rv, \ldots, rv^{i-1}$$
for period i, respectively.
- One dollar at time i has a present value of
$$f(r, v) \stackrel{\Delta}{=} \frac{P_1}{1+r} + \frac{P_2}{1+rv} + \frac{P_3}{1+rv^2} + \cdots + \frac{P_i}{1+rv^{i-1}}.$$

The BDT Model: Calibration (continued)

- By Eq. (147) on p. 1099, the yield volatility is

$$g(r, v) \triangleq \frac{1}{2} \ln \left(\frac{\left(\frac{P_{\mathrm{u},1}}{1+rv} + \frac{P_{\mathrm{u},2}}{1+rv^2} + \cdots + \frac{P_{\mathrm{u},i-1}}{1+rv^{i-1}} \right)^{-1/(i-1)} - 1}{\left(\frac{P_{\mathrm{d},1}}{1+r} + \frac{P_{\mathrm{d},2}}{1+rv} + \cdots + \frac{P_{\mathrm{d},i-1}}{1+rv^{i-2}} \right)^{-1/(i-1)} - 1} \right).$$

- Above, $P_{\mathrm{u},1}, P_{\mathrm{u},2}, \ldots$ denote the state prices at time $i-1$ of the subtree rooted at the up node (like $r_2 v_2$ on p. 1093).
- And $P_{\mathrm{d},1}, P_{\mathrm{d},2}, \ldots$ denote the state prices at time $i-1$ of the subtree rooted at the down node (like r_2 on p. 1093).

The BDT Model: Calibration (concluded)

- Note that every node maintains *three* state prices: $P_i, P_{\text{u},i}, P_{\text{d},i}$.
- Now solve

$$\begin{aligned} f(r, v) &= \frac{1}{(1+y)^i}, \\ g(r, v) &= \kappa_i, \end{aligned}$$

  for $r = r_i$ and $v = v_i$.
- This $O(n^2)$-time algorithm appears on p. 382 of the textbook.

Calibrating the BDT Model with the Differential Tree (in seconds)[a]

Number of years	Running time	Number of years	Running time	Number of years	Running time
3000	398.880	39000	8562.640	75000	26182.080
6000	1697.680	42000	9579.780	78000	28138.140
9000	2539.040	45000	10785.850	81000	30230.260
12000	2803.890	48000	11905.290	84000	32317.050
15000	3149.330	51000	13199.470	87000	34487.320
18000	3549.100	54000	14411.790	90000	36795.430
21000	3990.050	57000	15932.370	120000	63767.690
24000	4470.320	60000	17360.670	150000	98339.710
27000	5211.830	63000	19037.910	180000	140484.180
30000	5944.330	66000	20751.100	210000	190557.420
33000	6639.480	69000	22435.050	240000	249138.210
36000	7611.630	72000	24292.740	270000	313480.390

75MHz Sun SPARCstation 20, one period per year.

[a] Lyuu (1999).

The BDT Model: Continuous-Time Limit

- The continuous-time limit of the BDT model is[a]

$$d \ln r = \left(\theta(t) + \frac{\sigma'(t)}{\sigma(t)} \ln r \right) dt + \sigma(t) \, dW.$$

- The short rate volatility clearly should be a *declining* function of time for the model to display mean reversion.
  - That makes $\sigma'(t) < 0$.
- In particular, constant volatility will not attain mean reversion.

[a]Jamshidian (1991).

The Black-Karasinski Model[a]

- The BK model stipulates that the short rate follows

$$d \ln r = \kappa(t)(\theta(t) - \ln r)\, dt + \sigma(t)\, dW.$$

- This explicitly mean-reverting model depends on time through $\kappa(\cdot)$, $\theta(\cdot)$, and $\sigma(\cdot)$.
- The BK model hence has one more degree of freedom than the BDT model.
- The speed of mean reversion $\kappa(t)$ and the short rate volatility $\sigma(t)$ are independent.

---

[a] Black & Karasinski (1991).

The Black-Karasinski Model: Discrete Time

- The discrete-time version of the BK model has the same representation as the BDT model.
- To maintain a combining binomial tree, however, requires some manipulations.
- The next plot illustrates the ideas in which

$$\begin{aligned} t_2 &\stackrel{\Delta}{=} t_1 + \Delta t_1, \\ t_3 &\stackrel{\Delta}{=} t_2 + \Delta t_2. \end{aligned}$$

$$\begin{array}{ccccc}
 & & & \nearrow & \\
 & & \ln r_{\mathrm{d}}(t_2) & & \\
 & \nearrow & & \searrow & \\
\ln r(t_1) & & & & \ln r_{\mathrm{du}}(t_3) = \ln r_{\mathrm{ud}}(t_3) \\
 & \searrow & & \nearrow & \\
 & & \ln r_{\mathrm{u}}(t_2) & & \\
 & & & \searrow &
\end{array}$$

The Black-Karasinski Model: Discrete Time (continued)

- Note that

$$\begin{aligned}\ln r_{\mathrm{d}}(t_2) &= \ln r(t_1)+\kappa(t_1)(\theta(t_1)-\ln r(t_1))\,\Delta t_1-\sigma(t_1)\sqrt{\Delta t_1}\,,\\ \ln r_{\mathrm{u}}(t_2) &= \ln r(t_1)+\kappa(t_1)(\theta(t_1)-\ln r(t_1))\,\Delta t_1+\sigma(t_1)\sqrt{\Delta t_1}\,.\end{aligned}$$

- To make sure an up move followed by a down move coincides with a down move followed by an up move,

$$\begin{aligned}&\ln r_{\mathrm{d}}(t_2)+\kappa(t_2)(\theta(t_2)-\ln r_{\mathrm{d}}(t_2))\,\Delta t_2+\sigma(t_2)\sqrt{\Delta t_2}\,,\\ =\;&\ln r_{\mathrm{u}}(t_2)+\kappa(t_2)(\theta(t_2)-\ln r_{\mathrm{u}}(t_2))\,\Delta t_2-\sigma(t_2)\sqrt{\Delta t_2}\,.\end{aligned}$$

The Black-Karasinski Model: Discrete Time (continued)

- They imply
$$\kappa(t_2) = \frac{1 - (\sigma(t_2)/\sigma(t_1))\sqrt{\Delta t_2/\Delta t_1}}{\Delta t_2}. \tag{148}$$
- So from Δt_1, we can calculate the Δt_2 that satisfies the combining condition and then iterate.
  - $t_0 \to \Delta t_1 \to t_1 \to \Delta t_2 \to t_2 \to \Delta t_3 \to \cdots \to T$ (roughly).[a]

[a]As $\kappa(t), \theta(t), \sigma(t)$ are independent of r, the Δt_is will not depend on r.

The Black-Karasinski Model: Discrete Time (concluded)

- Unequal durations Δt_i are often necessary to ensure a combining tree.[a]

---

[a] Amin (1991); C. Chen (`R98922127`) (2011); Lok (`D99922028`) & Lyuu (2016, 2017).

Problems with Lognormal Models in General

- Lognormal models such as BDT and BK share the problem that $E^{\pi}[\,M(t)\,] = \infty$ for any finite t if they model the continuously compounded rate.[a]
- So periodically compounded rates should be modeled.[b]
- Another issue is computational.
- Lognormal models usually do not admit of analytical solutions to even basic fixed-income securities.
- As a result, to price short-dated derivatives on long-term bonds, the tree has to be built over the life of the underlying asset instead of the life of the derivative.

[a] Hogan & Weintraub (1993).
[b] Sandmann & Sondermann (1993).

Problems with Lognormal Models in General (concluded)

- This problem can be somewhat mitigated by adopting different time steps.[a]
  - Use a fine time step up to the maturity of the short-dated derivative.
  - Use a coarse time step beyond the maturity.
- A down side of this procedure is that it has to be tailor-made for each derivative.
- Finally, empirically, interest rates do not follow the lognormal distribution.

[a]Hull & White (1993).

The Extended Vasicek Model[a]

- Hull and White proposed models that extend the Vasicek model and the CIR model.
- They are called the extended Vasicek model and the extended CIR model.
- The extended Vasicek model adds time dependence to the original Vasicek model,

$$dr = (\theta(t) - a(t)\, r)\, dt + \sigma(t)\, dW.$$

- Like the Ho-Lee model, this is a normal model.
- The inclusion of $\theta(t)$ allows for an exact fit to the current spot rate curve.

[a]Hull & White (1990).

The Extended Vasicek Model (concluded)

- Function $\sigma(t)$ defines the short rate volatility, and $a(t)$ determines the shape of the volatility structure.
- Many European-style securities can be evaluated analytically.
- Efficient numerical procedures can be developed for American-style securities.

The Hull-White Model

- The Hull-White model is the following special case,

$$dr = (\theta(t) - ar)\,dt + \sigma\,dW.$$

- When the current term structure is matched,[a]

$$\theta(t) = \frac{\partial f(0,t)}{\partial t} + af(0,t) + \frac{\sigma^2}{2a}\left(1 - e^{-2at}\right).$$

[a] Hull & White (1993).

The Extended CIR Model

- In the extended CIR model the short rate follows

$$dr = (\theta(t) - a(t)\, r)\, dt + \sigma(t)\sqrt{r}\, dW.$$

- The functions $\theta(t)$, $a(t)$, and $\sigma(t)$ are implied from market observables.
- With constant parameters, there exist analytical solutions to a small set of interest rate-sensitive securities.

The Hull-White Model: Calibration[a]

- We describe a trinomial forward induction scheme to calibrate the Hull-White model given a and σ.
- As with the Ho-Lee model, the set of achievable short rates is evenly spaced.
- Let r_0 be the annualized, continuously compounded short rate at time zero.
- Every short rate on the tree takes on a value

$$r_0 + j\Delta r$$

for some integer j.

[a]Hull & White (1993).

The Hull-White Model: Calibration (continued)

- Time increments on the tree are also equally spaced at Δt apart.
- Hence nodes are located at times $i\Delta t$ for $i = 0, 1, 2, \ldots$.
- We shall refer to the node on the tree with

$$\begin{aligned} t_i &\stackrel{\Delta}{=} i\Delta t, \\ r_j &\stackrel{\Delta}{=} r_0 + j\Delta r, \end{aligned}$$

  as the (i, j) node.
- The short rate at node (i, j), which equals r_j, is effective for the time period $[\,t_i, t_{i+1})$.

The Hull-White Model: Calibration (continued)

- Use

$$\mu_{i,j} \stackrel{\Delta}{=} \theta(t_i) - a r_j \tag{149}$$

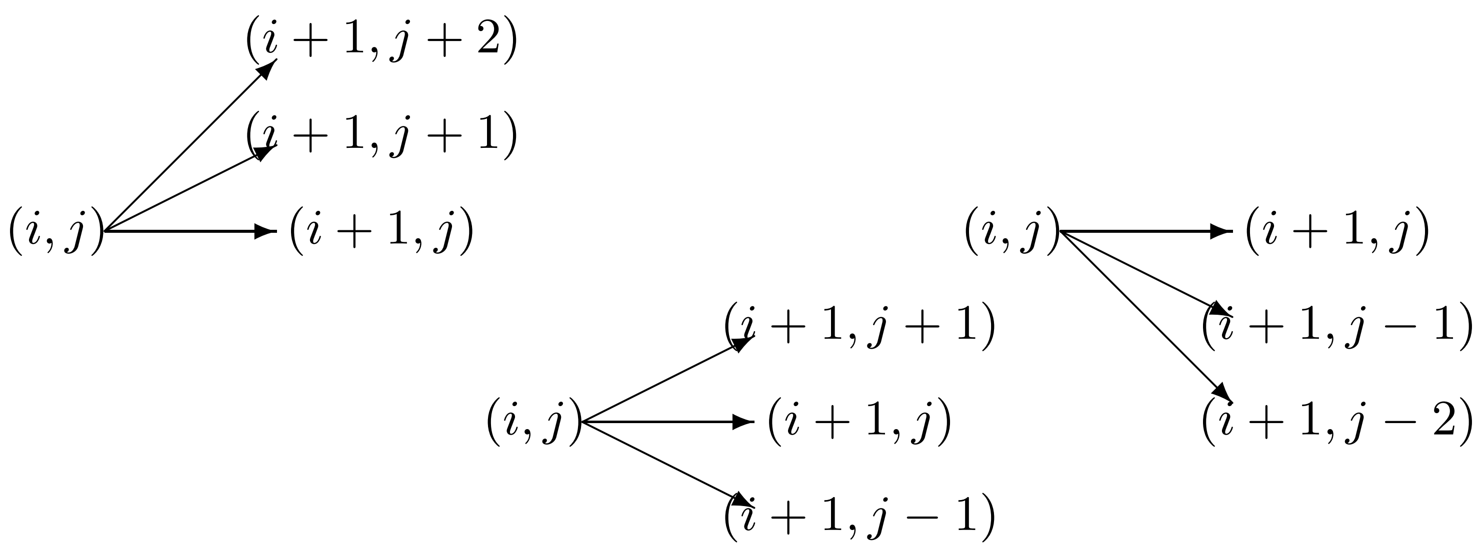
to denote the drift rate[a] of the short rate as seen from node (i, j).

- The three distinct possibilities for node (i, j) with three branches incident from it are displayed on p. 1121.

- The middle branch may be an increase of Δr, no change, or a decrease of Δr.

[a] Or, the annualized expected change.

The Hull-White Model: Calibration (continued)



The Hull-White Model: Calibration (continued)

- The upper and the lower branches bracket the middle branch.
- Define

$$
\begin{aligned}
p_1(i,j) &\stackrel{\Delta}{=} \text{the probability of following the upper branch from node } (i,j),\\
p_2(i,j) &\stackrel{\Delta}{=} \text{the probability of following the middle branch from node } (i,j),\\
p_3(i,j) &\stackrel{\Delta}{=} \text{the probability of following the lower branch from node } (i,j).
\end{aligned}
$$

- The root of the tree is set to the current short rate r_0.
- Inductively, the drift $\mu_{i,j}$ at node (i,j) is a function of (the still unknown) $\theta(t_i)$.
  - It describes the expected change from node (i,j).

The Hull-White Model: Calibration (continued)

- Once $\theta(t_i)$ is available, $\mu_{i,j}$ can be derived via Eq. (149) on p. 1120.
- This in turn determines the branching scheme at every node (i, j) for each j, as we will see shortly.
- The value of $\theta(t_i)$ must thus be made consistent with the spot rate $r(0, t_{i+2})$.[a]

[a] Not $r(0, t_{i+1})$!

The Hull-White Model: Calibration (continued)

- The branches emanating from node (i, j) with their probabilities[a] must be chosen to be consistent with $\mu_{i,j}$ and σ.
- This is done by letting the middle node be as closest to the current short rate r_j plus the drift $\mu_{i,j} \Delta t$.[b]

---

[a] $p_1(i, j)$, $p_2(i, j)$, and $p_3(i, j)$.

[b] A precursor of Lyuu and C. N. Wu's (R90723065) (2003, 2005) mean-tracking idea, which is the precursor of the binomial-trinomial tree of Dai (B82506025, R86526008, D8852600) & Lyuu (2006, 2008, 2010).

The Hull-White Model: Calibration (continued)

- Let k be the number among $\{ j-1, j, j+1 \}$ that makes the short rate reached by the middle branch, r_k, closest to

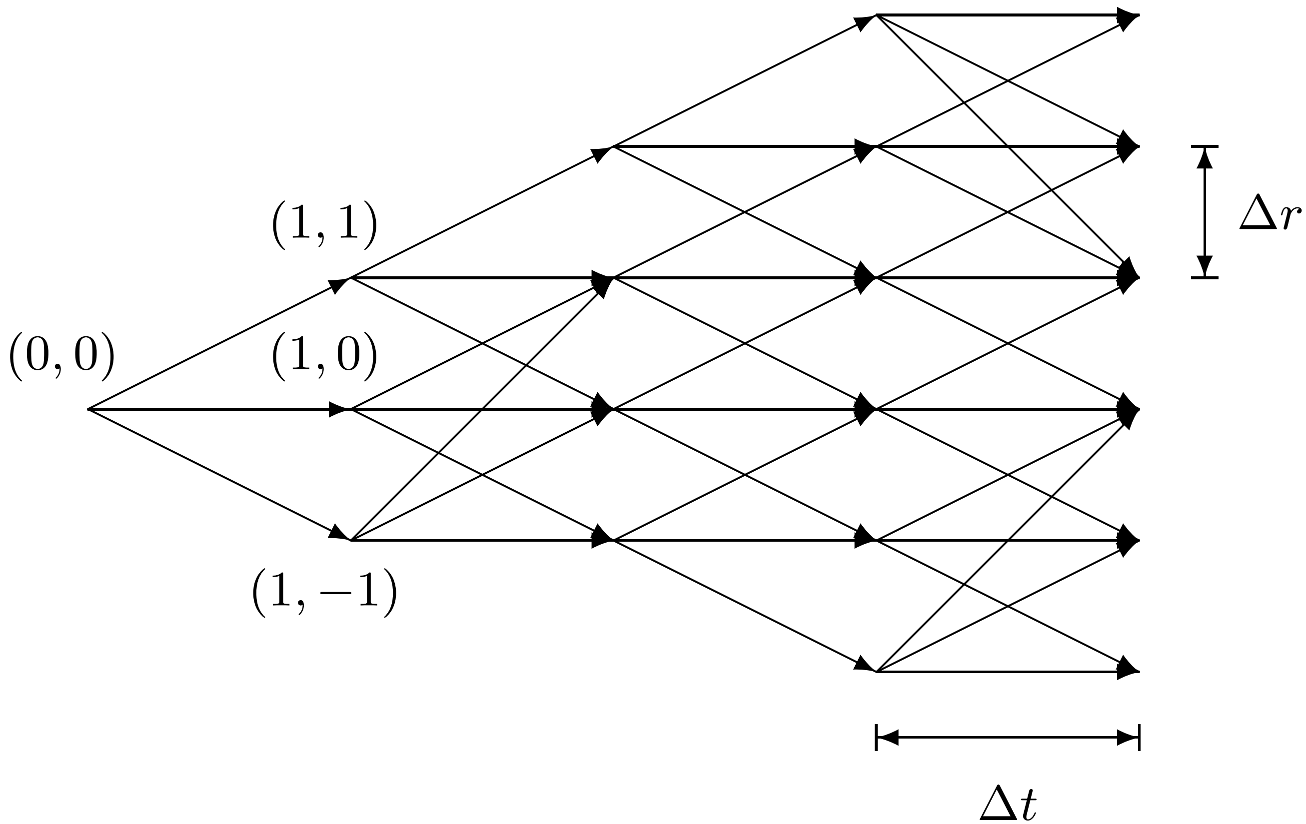
$$r_j + \mu_{i,j} \Delta t.$$

  - But note that $\mu_{i,j}$ is still *not* computed yet.

- Then the three nodes following node (i, j) are nodes

$$(i+1, k+1), (i+1, k), (i+1, k-1).$$

- See p. 1126 for a possible geometry.
- The resulting tree combines because of the constant jump sizes to reach k from j.


$(1,1)$
$(0,0)$
$(1,0)$
$(1,-1)$
Δr
Δt

The Hull-White Model: Calibration (continued)

- The probabilities for moving along these branches are functions of $\mu_{i,j}$, σ, j, and k:

$$p_1(i,j) = \frac{\sigma^2 \Delta t + \eta^2}{2(\Delta r)^2} + \frac{\eta}{2\Delta r} \tag{150}$$

$$p_2(i,j) = 1 - \frac{\sigma^2 \Delta t + \eta^2}{(\Delta r)^2} \tag{150$'$}$$

$$p_3(i,j) = \frac{\sigma^2 \Delta t + \eta^2}{2(\Delta r)^2} - \frac{\eta}{2\Delta r} \tag{150$''$}$$

where

$$\eta \stackrel{\Delta}{=} \mu_{i,j} \Delta t + (j-k)\, \Delta r.$$

The Hull-White Model: Calibration (continued)

- As trinomial tree algorithms are but explicit methods in disguise,[a] certain relations must hold for Δr and Δt to guarantee stability.
- It can be shown that their values must satisfy

$$\frac{\sigma\sqrt{3\Delta t}}{2} \leq \Delta r \leq 2\sigma\sqrt{\Delta t}$$

  for the probabilities to lie between zero and one.
  - For example, Δr can be set to $\sigma\sqrt{3\Delta t}$.[b]
- Now it only remains to determine $\theta(t_i)$.

---

[a] Recall p. 777.

[b] Hull & White (1988).

The Hull-White Model: Calibration (continued)

- At this point at time t_i,

$$r(0, t_1), r(0, t_2), \ldots, r(0, t_{i+1})$$

  have already been matched.

- Let $Q(i, j)$ be the state price at node (i, j).
- By construction, the state prices $Q(i, j)$ for all j are known by now.
- We begin with state price $Q(0, 0) = 1$.

The Hull-White Model: Calibration (continued)

- Let $\hat{r}(i)$ refer to the short rate value at time t_i.
- The value at time zero of a zero-coupon bond maturing at time t_{i+2} is then

$$
\begin{aligned}
& e^{-r(0,t_{i+2})(i+2)\,\Delta t} \\
= \; & \sum_j Q(i,j)\, e^{-r_j \Delta t}\, E^{\pi}\left[e^{-\hat{r}(i+1)\,\Delta t} \,\middle|\, \hat{r}(i) = r_j \right]. \qquad (151)
\end{aligned}
$$

- The right-hand side represents the value of \$1 obtained by holding a zero-coupon bond until time t_{i+1} and then reinvesting the proceeds at that time at the prevailing short rate $\hat{r}(i+1)$, which is stochastic.

The Hull-White Model: Calibration (continued)

- The expectation in Eq. (151) can be approximated by[a]

$$E^{\pi}\left[\, e^{-\hat{r}(i+1)\,\Delta t} \,\middle|\, \hat{r}(i) = r_j \right]$$

$$\approx \quad e^{-r_j \Delta t}\left(1 - \mu_{i,j}(\Delta t)^2 + \frac{\sigma^2(\Delta t)^3}{2}\right). \quad (152)$$

  – This solves the chicken-egg problem!

- Substitute Eq. (152) into Eq. (151) and replace $\mu_{i,j}$ with $\theta(t_i) - a r_j$ to obtain

$$\theta(t_i) \approx \frac{\sum_j Q(i,j)\, e^{-2 r_j \Delta t}\left(1 + a r_j (\Delta t)^2 + \sigma^2 (\Delta t)^3/2\right) - e^{-r(0,t_{i+2})(i+2)\,\Delta t}}{(\Delta t)^2 \sum_j Q(i,j)\, e^{-2 r_j \Delta t}}.$$

[a]See Exercise 26.4.2 of the textbook.

The Hull-White Model: Calibration (continued)

- For the Hull-White model, the expectation in Eq. (152) is actually known analytically by Eq. (26) on p. 165:

$$
\begin{aligned}
& E^{\pi}\left[e^{-\hat{r}(i+1)\,\Delta t} \,\middle|\, \hat{r}(i) = r_j \right] \\
= \quad & e^{-r_j \Delta t + (-\theta(t_i) + a r_j + \sigma^2 \Delta t/2)(\Delta t)^2}.
\end{aligned}
$$

- Therefore, alternatively,

$$
\theta(t_i) = \frac{r(0, t_{i+2})(i+2)}{\Delta t} + \frac{\sigma^2 \Delta t}{2} + \frac{\ln \sum_j Q(i,j)\, e^{-2 r_j \Delta t + a r_j (\Delta t)^2}}{(\Delta t)^2}.
$$

- With $\theta(t_i)$ in hand, we can compute $\mu_{i,j}$.[a]

[a]See Eq. (149) on p. 1120.

The Hull-White Model: Calibration (concluded)

- With $\mu_{i,j}$ available, we compute the probabilities.[a]
- Finally the state prices at time t_{i+1}:

$$Q(i+1, j) = \sum_{(i, j^*) \text{ is connected to } (i+1, j) \text{ with probability } p_{j^*}} p_{j^*} e^{-r_{j^*} \Delta t} Q(i, j^*).$$

- There are at most 5 choices for j^* (why?).
- The total running time is $O(n^2)$.
- The space requirement is $O(n)$ (why?).

---

[a]See Eqs. (150) on p. 1127.

Comments on the Hull-White Model

- One can try different values of a and σ for each option.
- Or have an a value common to all options but use a different σ value for each option.
- Either approach can match all the option prices exactly.
- But suppose the demand is for a single set of parameters that replicate *all* option prices.
- Then the Hull-White model can be calibrated to all the observed option prices by choosing a and σ that minimize the mean-squared pricing error.[a]

[a] Hull & White (1995).

The Hull-White Model: Calibration with Irregular Trinomial Trees

- The previous calibration algorithm is quite general.
- For example, it can be modified to apply to cases where the diffusion term has the form σr^b.
- But it has at least two shortcomings.
- First, the resulting trinomial tree is irregular (p. 1126).
  - So it is harder to program (for nonprogrammers).
- The second shortcoming is again a consequence of the tree's irregular shape.

The Hull-White Model: Calibration with Irregular Trinomial Trees (concluded)

- Recall that the algorithm figured out $\theta(t_i)$ that matches the spot rate $r(0, t_{i+2})$ in order to determine the branching schemes for the nodes at time t_i.
- But without those branches, the tree was not specified, and backward induction on the tree was not possible.
- To avoid this chicken-egg dilemma, the algorithm turned to the continuous-time model to evaluate Eq. (151) on p. 1130 that helps derive $\theta(t_i)$.
- The resulting $\theta(t_i)$ hence might not yield a tree that matches the spot rates exactly.

Finis