MAFS5250 – Computational Methods for Pricing Structured Products

Topic 1 – Lattice tree methods

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1.1 Binomial option pricing models

From replication to risk neutral valuation

Discrete model of the dynamics of the underlying price process

Under the binomial random walk model, the asset prices after one period $\Delta t$ will be either $uS$ or $dS$ with probability $q$ and $1 - q$, respectively.

We assume $u > 1 > d$ so that $uS$ and $dS$ represent the up-move and down-move of the asset price, respectively. The proportional jump parameters $u$ and $d$ will be related to the asset price dynamics.

Let $R$ denote the growth factor of riskless investment over one period so that $1$ invested in a riskfree money market account will grow to $R$ after one period. In order to avoid riskless arbitrage opportunities, we must have $u > R > d$. 

Construction of a replicating portfolio

By buying the asset and borrowing cash (in the form of riskfree money market account) in appropriate proportions, one can replicate the position of a call.

Suppose we form a portfolio which consists of \( \alpha \) units of asset and cash amount \( M \) in the form of riskless investment (money market account). After one period of time \( \Delta t \), the value of the portfolio becomes

\[
\begin{cases} 
\alpha u S + RM & \text{with probability } q \\
\alpha d S + RM & \text{with probability } 1 - q.
\end{cases}
\]

Note that we happen to have 2 investment instruments: risky asset and money market account and 2 states of the world: up and down in the binomial model. Under this special scenario, the replication approach of deriving the binomial pricing formula works.
The portfolio is used to replicate the long position of a call option on a non-dividend paying asset.

As there are two possible states of the world: asset price goes up or down, the call price is dependent on asset price, thus it is a contingent claim.

Suppose the current time is only one period $\Delta t$ prior to expiration. Let $c$ denote the current call price, and $c_u$ and $c_d$ denote the call price after one period (which is the expiration time in the present context) corresponding to the up-move and down-move of the asset price, respectively.
Let $X$ denote the strike price of the call. The payoff of the call at expiry is given by

\[
\begin{align*}
    &c_u = \max(uS - X, 0) \quad \text{with probability } q \\
    &c_d = \max(dS - X, 0) \quad \text{with probability } 1 - q.
\end{align*}
\]

Evolution of the asset price $S$ and the money market account $M$ after one time period under the binomial model. The risky asset value may either go up to $uS$ or go down to $dS$, while the riskless investment amount $M$ grows to $RM$ with certainty.
Replicating procedure

The above portfolio containing the risky asset and money market account is said to replicate the long position of the call if and only if the values of the portfolio and the call option match for each possible outcome, that is,

\[ \alpha u S + RM = c_u \quad \text{and} \quad \alpha d S + RM = c_d. \]

Solving the pair of equations, we obtain

\[ \alpha = \frac{c_u - c_d}{(u - d) S} \geq 0, \quad M = \frac{uc_d - dc_u}{(u - d) R} \leq 0. \]

Apparently, we have 2 states of the world that generate 2 equations via matching the outcomes. There are two unknowns \( \alpha \) and \( M \) to be determined, so we have equal number of states and unknowns.

- The uninteresting case occurs when \( c_u = c_d = 0 \). This leads to \( \alpha = M = 0 \). If the call is surely to be out-of-the-money under the two possible states, then its present value is zero.
Since $\alpha$ is always non-negative and $M$ is always non-positive, the replicating portfolio involves buying the asset and borrowing cash in the corresponding proportions (excluding the degenerate case of $\alpha = M = 0$).

The number of units of asset held is seen to be the ratio of the difference of call values $c_u - c_d$ to the difference of asset values $uS - dS$. This is called the hedge ratio.

The call option can be replicated by a portfolio of the two basic securities: risky asset and riskfree money market account. By invoking the law of one price, the call value is identical to the value of the replicating portfolio.

**Query:** Can we adopt the above replicating procedure if the discrete asset price process follows the trinomial random walk model (3 states of the world in the next move)?

**Answer:** One has to use the risk neutral valuation principle for deriving the trinomial pricing formula.
Binomial option pricing formula

The current value of the call is given by the current value of the replicating portfolio, that is,

\[ c = \alpha S + M = \frac{R-d}{u-d} c_u + \frac{u-R}{u-d} c_d \]

\[ = \frac{pc_u + (1-p)c_d}{R} \]

where \( p = \frac{R-d}{u-d} \).

Note that the probability \( q \), which is the subjective probability of up-move or down-move of the asset price, does not appear in the call value.

The parameter \( p \) can be shown to be \( 0 < p < 1 \) since \( u > R > d \) and so \( p \) can be interpreted as a probability.
Risk neutral pricing measure

From the relation

$$puS + (1 - p)dS = \frac{R - d}{u - d} uS + \frac{u - R}{u - d} dS = RS,$$

one can interpret the result as follows: the expected rate of returns on the asset with $p$ as the probability of upside move is just equal to the riskless interest rate. In other words, we observe

$$S = \frac{1}{R} E^*[S^{\Delta t} | S],$$

where $E^*$ is expectation under this probability measure. We may view $p$ as the risk neutral probability that the asset price goes up in the next move.

Since $E^* \left[ \frac{S^{\Delta t}}{R} | S \right]$ equals the current asset value $S$, we say that the discounted asset value process is a martingale under the risk neutral pricing measure.
**Discounted expectation of the terminal payoff**

The call price can be interpreted as the expectation of the payoff of the call option at expiry under the risk neutral probability measure discounted at the riskless interest rate.

The binomial call value formula can be expressed as

$$c = \frac{1}{R} E^* [c^{\Delta t} | S],$$

where $c$ denotes the call value at the current time, and $c^{\Delta t}$ denotes the random variable representing the call value one period later.

Besides applying the *principle of replication of claims*, the binomial option pricing formula can also be derived using the *riskless hedging principle* (similar to the derivation of the continuous Black-Scholes equation) or finding the *state prices* of the up-state and down-state.
Determination of the jump parameters ($u$ and $d$) via the asset price dynamics

- The jump parameters are related to the variance of the discounted asset value process under the risk neutral measure.
- For the continuous asset price dynamics of Geometric Brownian motion under the risk neutral measure, we have

$$d \ln S_t = \left( r - \frac{\sigma^2}{2} \right) dt + \sigma dZ_t$$

so that $\ln \frac{S_{t+\Delta t}}{S_t}$ becomes normally distributed with mean $\left( r - \frac{\sigma^2}{2} \right) \Delta t$ and variance $\sigma^2 \Delta t$, where $r$ is the riskless interest rate and $\sigma^2$ is the variance rate.
- Expressed in the form of the exponentiation of a normal random variable, the mean and variance of $\frac{S_{t+\Delta t}}{S_t}$ are $R$ and $R^2(e^{\sigma^2 \Delta t} - 1)$, respectively, where $R = e^{r \Delta t}$.
• For the one-period binomial option model under the risk neutral measure, the mean and variance of the asset price ratio \( \frac{S_{t+\Delta t}}{S_t} \) are

\[
p u + (1 - p) d \quad \text{and} \quad p u^2 + (1 - p) d^2 - [p u + (1 - p) d]^2,
\]
respectively.

• By equating the mean and variance of the asset price ratio in both the continuous and discrete models, we obtain

\[
E[S^{\Delta t}] = p u + (1 - p) d = R
\]
\[
E[(S^{\Delta t})^2] - \{E[S^{\Delta t}]\}^2 = p u^2 + (1 - p) d^2 - R^2 = R^2(e^{\sigma^2 \Delta t} - 1).
\]
The first equation leads to \( p = \frac{R - d}{u - d} \), the usual risk neutral probability.
A convenient choice of the third condition is the *tree-symmetry condition*

\[ u = \frac{1}{d}, \]

so that the lattice nodes associated with the binomial tree are symmetrical.

Writing \( \sigma^2 = R^2 e^{\sigma^2 \Delta t} \), the solution is found to be

\[ u = \frac{1}{d} = \frac{\bar{\sigma}^2 + 1 + \sqrt{(\bar{\sigma}^2 + 1)^2 - 4R^2}}{2R}, \quad p = \frac{R - d}{u - d}. \]

How to obtain a nice approximation function to \( u \) instead of using the above daunting expression?
By expanding $u$ in Taylor series in powers of $\sqrt{\Delta t}$, we obtain

$$u = 1 + \sigma \sqrt{\Delta t} + \frac{\sigma^2}{2} \Delta t + \frac{4r^2 + 4\sigma^2 r + 3\sigma^4}{8\sigma} \Delta t^2 + O(\Delta t^3).$$

Observe that the first three terms in the above Taylor series agree with those of $e^{\sigma \sqrt{\Delta t}}$ up to $O(\Delta t)$ term.

This suggests the judicious choice of the following set of parameter values

$$u = e^{\sigma \sqrt{\Delta t}}, \quad d = e^{-\sigma \sqrt{\Delta t}}, \quad p = \frac{R - d}{u - d}.$$

With this new set of parameters, the variance of the price ratio $\frac{S_{t+\Delta t}}{S_t}$ in the continuous and discrete models agree up to $O(\Delta t)$.

If we write $\Delta x$ as the change in the log asset price ratio over $\Delta t$, then $u = e^{\sigma \sqrt{\Delta t}}$ is equivalent to $\Delta x = \sigma \sqrt{\Delta t}$. This is consistent with the Brownian increment $\Delta x$ over the differential time interval $\Delta t$. 
Continuous limit of the binomial model

We consider the asymptotic limit $\Delta t \to 0$ of the binomial formula

$$c = [pc_u^\Delta t + (1 - p)c_d^\Delta t] e^{-r\Delta t}.$$ 

In the continuous analog, the binomial formula can be written as

$$c(S, t - \Delta t) = [pc(uS, t) + (1 - p)c(dS, t)] e^{-r\Delta t}.$$ 

Instead of choosing $c(uS, t + \Delta t)$ and $c(dS, t + \Delta t)$ in the formula, the above form is more convenient for subsequent analytic derivation since cross derivative terms do not appear in the later Taylor expansion procedure. Assuming sufficient continuity of $c(S, t)$, we perform the Taylor expansion of the binomial scheme at $(S, t)$ as follows:
\[-c(S, t - \triangle t) + [pc(uS, t) + (1 - p)c(dS, t)]e^{-r\triangle t} \]
\[= \frac{\partial c}{\partial t}(S, t)\triangle t - \frac{1}{2}\frac{\partial^2 c}{\partial t^2}(S, t)\triangle t^2 + \cdots - (1 - e^{-r\triangle t})c(S, t) \]
\[+ e^{-r\triangle t}\left\{[p(u - 1) + (1 - p)(d - 1)]S\frac{\partial c}{\partial S}(S, t) \right. \]
\[+ \frac{1}{2}[p(u - 1)^2 + (1 - p)(d - 1)^2]S^2\frac{\partial^2 c}{\partial S^2}(S, t) \]
\[+ \frac{1}{6}[p(u - 1)^3 + (1 - p)(d - 1)^3]S^3\frac{\partial^3 c}{\partial S^3}(S, t) + \cdots \right\}. \]

First, we observe that

\[1 - e^{-r\triangle t} = r\triangle t + O(\triangle t^2), \]

and also

\[e^{-r\triangle t}[p(u - 1) + (1 - p)(d - 1)] = r\triangle t + O(\triangle t^2), \]
\[e^{-r\triangle t}[p(u - 1)^2 + (1 - p)(d - 1)^2] = \sigma^2\triangle t + O(\triangle t^2), \]
\[e^{-r\triangle t}[p(u - 1)^3 + (1 - p)(d - 1)^3] = O(\triangle t^2). \]
Combining the results, we obtain

\[
-c(S, t - \Delta t) + [p c(uS, t) + (1-p) c(dS, t)] e^{-r\Delta t} = \left[ \frac{\partial c}{\partial t}(S, t) + rS \frac{\partial c}{\partial S}(S, t) + \frac{\sigma^2}{2} S^2 \frac{\partial^2 c}{\partial S^2}(S, t) - rc(S, t) \right] \Delta t + O(\Delta t^2).
\]

Since \( c(S, t) \) satisfies the binomial formula, so we obtain

\[
0 = \frac{\partial c}{\partial t}(S, t) + rS \frac{\partial c}{\partial S}(S, t) + \frac{\sigma^2}{2} S^2 \frac{\partial^2 c}{\partial S^2}(S, t) - rc(S, t) + O(\Delta t).
\]

In the limit \( \Delta t \to 0 \), the binomial call value \( c(S, t) \) satisfies the Black-Scholes equation.
**Multiperiod extension**

Let $c_{uu}$ denote the call value at two periods beyond the current time with two consecutive upward moves of the asset price and similar notational interpretation for $c_{ud}$ and $c_{dd}$. The call values $c_u$ and $c_d$ are related to $c_{uu}$, $c_{ud}$ and $c_{dd}$ as follows:

$$c_u = \frac{p c_{uu} + (1 - p) c_{ud}}{R} \quad \text{and} \quad c_d = \frac{p c_{ud} + (1 - p) c_{dd}}{R}.$$  

The call value at the current time which is two periods from expiry is found to be

$$c = \frac{p^2 c_{uu} + 2p(1 - p) c_{ud} + (1 - p)^2 c_{dd}}{R^2},$$

where the corresponding terminal payoff values are given by

$$c_{uu} = \max(u^2 S - X, 0), \quad c_{ud} = \max(udS - X, 0), \quad c_{dd} = \max(d^2 S - X, 0).$$
The coefficients \( p^2, 2p(1-p) \) and \((1-p)^2\) represent the respective risk neutral probability of having two up jumps, one up jump and one down jump, and two down jumps in the two consecutive moves of the binomial process.

Dynamics of asset price and call price in a two-period binomial model
With \( n \) binomial steps, the risk neutral probability of having \( j \) up jumps and \( n-j \) down jumps is given by \( \binom{n}{j} p^j (1-p)^{n-j} \), \( j = 0, 1, \ldots, n \), where \( \binom{n}{j} = \frac{n!}{j!(n-j)!} \) is the binomial coefficient.

The corresponding terminal payoff when \( j \) up jumps and \( n-j \) down jumps occur is seen to be \( \max(u^j d^{n-j} S - X, 0) \).

By the risk neutral valuation principle, the call value obtained from the \( n \)-period binomial model is given by

\[
c = \frac{\sum_{j=0}^{n} \binom{n}{j} p^j (1-p)^{n-j} \max(u^j d^{n-j} S - X, 0)}{R^n}.
\]
How to get rid of the “max” function in the option type payoff function?

We define \( k \) to be the smallest non-negative integer such that \( u^k d^{n-k} S \geq X \), that is, \( k \geq \frac{\ln \frac{X}{S d^n}}{\ln \frac{u}{d}} \). It is seen that

\[
\max(u^j d^{n-j} S - X, 0) = \begin{cases} 
0 & \text{when } j < k \\
u^j d^{n-j} S - X & \text{when } j \geq k 
\end{cases}
\]

The integer \( k \) gives the minimum number of upward moves required for the asset price in the multiplicative binomial process in order that the call expires in-the-money.

The call price formula can be simplified as

\[
c = S \sum_{j=k}^{n} C_j \cdot p^j (1 - p)^{n-j} \frac{u^j d^{n-j}}{R^n} - X R^{-n} \sum_{j=k}^{n} C_j \cdot p^j (1 - p)^{n-j}.
\]
Interpretation of the call price formula

The last term in above equation can be interpreted as the expectation value of the payment made by the holder at expiration discounted by the factor $R^{-n}$, and $\sum_{j=k}^{n} C_{j}^{n} p^{j} (1 - p)^{n-j}$ is seen to be the probability under the risk neutral measure that the call expires in-the-money.

The above probability is related to the *complementary binomial distribution function* defined by

$$\Phi(n, k, p) = \sum_{j=k}^{n} C_{j}^{n} p^{j} (1 - p)^{n-j}.$$ 

Note that $\Phi(n, k, p)$ gives the probability for achieving at least $k$ successes in $n$ trials of a binomial experiment, where $p$ is the probability of success in each trial.
Further, if we write $p' = \frac{up}{R}$ so that $1 - p' = \frac{d(1-p)}{R}$, then the call price formula for the $n$-period binomial model can be expressed as

$$c = S\Phi(n, k, p') - XR^{-n}\Phi(n, k, p).$$

- The first term gives the discounted expectation of the terminal asset price given that the call expires in-the-money.
- The second term gives the present value of the expected cost incurred by exercising the call.
- In the replicating portfolio, we require long holding of $\Phi(n, k, p')$ units of the underlying asset and short holding of $XR^{-n}\Phi(n, k, p)$ dollars of the money market account.
- The parameter $n$ is related to time to expiry. The another parameter $k$ is related to expectation of being in-the-money at expiry, which exhibits implicit dependence on volatility (via $u$ and $d$) and strike price $X$. 
Mathematical representation

The call price for the $n$-period binomial model can be expressed as the discounted expectation of the terminal payoff under the risk neutral measure

$$c = \frac{1}{R^n} E^* [c_T] = \frac{1}{R^n} E^* [\max(S_T - X, 0)], \quad T = t + n\Delta t,$$

where $c_T$ is the terminal payoff, $\max(S_T - X, 0)$, of the call at expiration time $T$ and $\frac{1}{R^n}$ is the discount factor over $n$ periods. That is,

$$S\Phi(n, k, p') = \frac{1}{R^n} E^*[S_T \mathbf{1}_{\{S_T > X\}}]$$

$$\Phi(n, k, p) = E^*[\mathbf{1}_{\{S_T > X\}}] = P^*[S_T > X].$$

The expectation operator $E^*$ is taken under the risk neutral measure rather than the subjective probability measure associated with the actual (physical) asset price process.
Dynamic programming procedure for pricing an American option

How to price in the early exercise feature in an American option?

Without the early exercise privilege, risk neutral valuation leads to the usual binomial formula

\[ V_{cont} = \frac{pV_u^{\Delta t} + (1 - p)V_d^{\Delta t}}{R}. \]

To reflect the optimal decision of either continuing to hold the American option or exercising the option, the following dynamic programming procedure is applied at each binomial node

\[ V = \max(V_{cont}, h(S)), \]

where \( h(S) \) is the exercise payoff when the asset price assumes the value \( S \). The stochastic optimization of the optimal stopping rule (early exercise feature) associated with an American option can be realized by the dynamic programming procedure applied at each binomial node.
American put option

The intrinsic value of a vanilla put option is $X - S^m_j$ at the $(n, j)$ node, where $X$ is the strike price. Here, $n$ is the number of time steps from the tip of the binomial tree and $j$ is the number of up-moves among the $n$ steps. The dynamic programming procedure applied at each node is given by

$$P^n_j = \max \left( \frac{pP^{n+1}_{j+1} + (1-p)P^{n+1}_j}{R}, X - S^m_j \right),$$

where $n = N - 1, \ldots, 0$, and $j = 0, 1, \ldots, n$. Here, $N$ is the total number of time steps in the binomial tree.
Example 1 – Pricing an American put option

Consider a 5-month American put option on a non-dividend-paying stock when the stock price is $50, the strike price is $50, the risk-free interest rate is 10% per annum, and the volatility is 40% per annum. That is, \( S = 50, X = 50, r = 0.10, \sigma = 0.40, T = 0.4167 \).

Suppose that we divide the life of the option into five intervals of length of 1 month (= 0.0833 year) for the purpose of constructing a binomial tree.

With \( \Delta t = 0.0833 \), we have

\[
\begin{align*}
    u &= e^{\sigma \sqrt{\Delta t}} = 1.1224, \\
    d &= e^{-\sigma \sqrt{\Delta t}} = 0.8909, \\
    R &= e^{r \Delta t} = 1.0084, \\
    p &= \frac{R - d}{u - d} = 0.5073, \quad 1 - p = 0.4927.
\end{align*}
\]
At each node:

Upper value = Underlying Asset Price

Lower value = Option Price

Shading indicates the node at which the option is exercised

Strike price = 50

Discount factor per step = $1/R = e^{-r\Delta t} = 0.9917$

Time step, $\Delta t = 0.0833$ years, 30.42 days

Growth factor per step, $R = 1.0084$

Risk neutral probability of up-move, $p = 0.5073$

Proportional up-jump factor, $u = 1.1224$

Proportional down-jump factor, $d = 1/u = 0.8909$
• The stock price at the \( j \)th node \((j = 0, 1, \cdots , n)\) at time \( n\Delta t \) \((n = 0, 1, \cdots , 5)\) is calculated as \( S_0w^j d^{n-j} \). For example, the stock price at node \( A \) \((n = 4, j = 1)\) (i.e., the second node up at the end of the fourth time step) is \( 50 \times 1.1224 \times 0.8909^3 = $39.69 \).

• The option prices at the final nodes are calculated as \( \max(X - S_T, 0) \). For example, the option price at node \( G \) is \( 50.00 - 35.36 = 14.64 \).

**Backward induction procedure**

• First, we assume no exercise of the option at the nodes. This means that the option price is calculated as the present value of the expected option price one time step later. For example, at node \( E \), the option price is calculated as

\[
(0.5073 \times 0 + 0.4927 \times 5.45)e^{-0.10 \times 0.0833} = 2.66
\]

whereas at node \( A \) it is calculated as

\[
(0.5073 \times 5.45 + 0.4927 \times 14.64)e^{-0.10 \times 0.0833} = 9.90.
\]
Check to see if early exercise is preferable to waiting

- At node $E$, early exercise would give a value for the option of zero because both the stock price and strike price are $50. Clearly it is best to wait. The correct value for the option at node $E$, therefore, is $2.66.

- At node $A$, it is a different story. If the option is exercised, it is worth $50.00 - 39.69$, or $10.31$. This is more than $9.90$. If node $A$ is reached, then the option should be exercised and the correct value for the option at node $A$ is $10.31$.

- Option prices at earlier nodes are calculated in a similar way. Note that it is not always best to exercise an option early even when it is in the money at that node.
Consider node $B$, the American put is in-the-money since the asset price $39.69$ is below $50$. If the option is exercised, it is worth $50.00 - 39.69$, or $10.31$. However, if it is held, it is worth

$$(0.5073 \times 6.38 + 0.4927 \times 14.64)e^{-0.10 \times 0.0833} = 10.36.$$

The option should not be exercised at this node, and the correct option value at the node is $10.36$.

- Working back through the tree, the value of the option at the initial node is $4.49$. This is our numerical estimate for the option’s current value.

- In practice, a smaller value of $\Delta t$, and many more nodes, would be used. With $30, 50, 100$, and $500$ time steps we obtain values for the option of $4.263, 4.272, 4.278$, and $4.283$. 

Convergence of the price of the option with respect to increasing number of time steps

The convergence trend is oscillatory. Overshooting the theoretical true value at the current choice of the time step becomes undershooting when the number of time steps is increased by one.
Early exercise boundary $S_P^*(\tau)$

The optimal exercise policy is characterized by the early exercise curve $S_P^*(\tau)$, where the American put option should be exercised when the stock price falls below the critical threshold value $S_P^*(\tau)$ for a given time to expiry $\tau$. 

![Diagram](image-url)
• The numerical approximation of $S^*_P(\tau)$ can be deduced from the binomial tree calculations by recording the node points at which the American put value assumes the exercise payoff.

• The early exercise boundary is approximated by taking the (arithmetic or geometric) average of the asset prices at neighboring nodes at the same time level at which continuation value is taken at the upper node while exercise value is taken at the lower node.

• As a numerical example (refer to the numerical results shown on p.29), we approximate the early exercise boundary at $t = 0.25, t = 0.3333$ and $t = 0.4167$ as $\frac{44.55+35.36}{2}$ or $\sqrt{44.55 \times 35.36}$, $\frac{50.00+39.69}{2}$ or $\sqrt{50.00 \times 39.69}$, $\frac{56.12+44.55}{2}$ or $\sqrt{56.12 \times 44.55}$, respectively.
Callable American call – game option between the issuer and holder

- The callable feature entitles the issuer to buy back the American option at any time at a predetermined call price.
- Upon call, the holder can choose either to exercise the call or receive the call price as cash.
- Let the call price be $K$. The dynamic programming procedure applied at each node to model the game between the issuer and holder can be constructed as follows:

$$ C_j^m = \min \left( \max \left( \frac{pC_{j+1}^{m+1} + (1 - p)C_{j}^{m+1}}{R}, S_j^m - X \right), \max(K, S_j^m - X) \right). $$
Justification of the dynamic programming procedure

- The first term \( \max \left( \frac{pC^{n+1}_{n+1} + (1 - p)C^{n+1}_j}{R}, S^n_j - X \right) \) represents the optimal strategy of the holder, given no call of the option by the issuer.

- Upon call by the issuer, the payoff is given by the second term \( \max(K, S^n_j - X) \) since the holder can either receive cash amount \( K \) or exercise the option.

- From the perspective of the issuer, he chooses to call or restrain from calling so as to minimize the option value with reference to the possible actions of the holder. The value of the callable call is given by taking the minimum value of the above two terms.
Recall the well known distributive rule: \( \alpha x + \alpha y = \alpha(x + y) \). In the current context, we may treat “taking max” as multiplication and “taking min” as addition. An equivalent dynamic programming procedure can be constructed as follows:

\[
C^m_j = \max \left( S^n_j - X, \min \left( \frac{pC_{j+1}^m + (1 - p)C_{j+1}^m}{R}, K \right) \right).
\]

- From financial intuition, the option will be called when the continuation value is above the call price \( K \). Independent of whether the option to be either called or not called, the holder can always choose to exercise to receive \( S^n_j - X \) if the exercise payoff has a higher value.
Estimating delta and other Greek letters

• The delta (Δ) of an option is the rate of change of its price with respect to the underlying stock price. It can be calculated as

\[
\frac{\Delta f}{\Delta S}
\]

where \( \Delta S \) is a small change in the stock price and \( \Delta f \) is the corresponding small change in the option price.

• At time \( \Delta t \), we have an estimate \( f_{11} \) for the option price when the stock price is \( S_0u \) and an estimate \( f_{10} \) for the option price when the stock price is \( S_0d \).

• When \( \Delta S = S_0u - S_0d \), \( \Delta f = f_{11} - f_{10} \). Therefore an estimate of delta at time \( \Delta t \) is

\[
\Delta = \frac{f_{11} - f_{10}}{S_0u - S_0d}.
\]
Gamma calculations

To determine gamma (Γ), note that we have two estimates of ∆ at time 2Δt.

When \( S = \frac{S_0 u^2 + S_0}{2} \) (halfway between the second and third node), delta is \( \frac{(f_{22} - f_{21})}{(S_0 u^2 - S_0)} \); when \( S = \frac{S_0 + S_0 d^2}{2} \) (halfway between the first and second node), delta is \( \frac{(f_{21} - f_{20})}{(S_0 - S_0 d^2)} \).

The difference between the two values of \( S \) is \( h \), where
\[
h = 0.5(S_0 u^2 - S_0 d^2).
\]

Gamma is the change in delta divided by \( h \):
\[
\Gamma = \frac{\frac{(f_{22} - f_{21})}{(S_0 u^2 - S_0)} - \frac{(f_{21} - f_{20})}{(S_0 - S_0 d^2)}}{h}.
\]
**Theta calculations**

Theta is the rate of change of the option price with time when all else is kept constant. If the tree starts at time zero, an estimate of theta is

$$\Theta = \frac{f_{21} - f_{00}}{2\Delta t}.$$  

Note that $f_{21}$ is the option value at two time steps from time zero and with the same asset price.

**Vega calculations**

Vega can be calculated by making a small change, $\Delta \sigma$, in the volatility and constructing a new tree to obtain a new value of the option. The time step $\Delta t$ should be kept the same. The estimate of vega is

$$\nu = \frac{f^* - f}{\Delta \sigma},$$

where $f$ and $f^*$ are the estimates of the option price from the original and the new tree, respectively.
Example 2

- Consider again Example 1. We have $f_{1,0} = 6.96$ and $f_{1,1} = 2.16$. An estimate for delta is given by
  \[ \frac{2.16 - 6.96}{56.12 - 44.55} = -0.41. \]

- An estimate of the gamma of the option can be obtained from the values at nodes $B, C,$ and $F$ as
  \[ \frac{[(0.64 - 3.77)/(62.99 - 50.00)] - [(3.77 - 10.36)/(50.00 - 39.66)]}{11.65} = 0.03. \]

- An estimate of the theta of the option can be obtained from the values at nodes $D$ and $C$ as
  \[ \frac{3.77 - 4.49}{0.1667} = -4.3 \text{ per year} \]
  or $-0.012 \text{ per calendar day}.$

- These are only rough estimates. They become progressively better as the number of time steps on the tree is increased.
Discrete dividend models

Let $S$ be the asset price at the current time which is $n\Delta t$ from expiry, and suppose a discrete dividend of amount $D$ is paid at time between one time step and two time steps from the current time.

Consider the naive construction of the binomial tree. The nodes in the binomial tree at two time steps from the current time would correspond to asset prices

$$u^2 S - D, \quad S - D \quad \text{and} \quad d^2 S - D,$$

since the asset price drops by the same amount as the dividend right after the dividend payment.
Extending one time step further, there will be six nodes

\[(u^2S - D)u, (u^2S - D)d, (S - D)u, (S - D)d, (d^2S - D)u, (d^2S - D)d\]

instead of four nodes as in the usual binomial tree without discrete dividend.

This is because \((u^2S - D)d \neq (S - D)u\) and \((S - D)d \neq (d^2S - D)u\), so the interior nodes do not recombine.

In general, suppose a discrete dividend is paid in the future between \((k-1)^{th}\) and \(k^{th}\) time step, then at the \((k+m)^{th}\) time step, the number of nodes would be \((m + 1)(k + 1)\) rather than \(k + m + 1\) nodes as in the usual reconnecting binomial tree.
Binomial tree with single discrete dividend
Splitting the asset price into the deterministic dividends component and risky component

- Splitting the asset price $S_t$ into two parts: the risky component $\tilde{S}_t$ that is stochastic and the remaining part that will be used to pay the discrete dividend (assumed to be deterministic) in the future.

- Suppose the dividend date is $t^*$, then at the current time $t$, the risky component $\tilde{S}_t$ is given by

  \[
  \tilde{S}_t = \begin{cases} 
  S_t - De^{-(t^*-t)}, & t < t^* \\
  S_t, & t > t^*.
  \end{cases}
  \]

- Let $\tilde{\sigma}$ denote the volatility of $\tilde{S}_t$ and assume $\tilde{\sigma}$ to be constant rather than the volatility of $S_t$ itself to be constant.
• Assume that a discrete dividend $D$ is paid at time $t^*$, which lies between the $k^{th}$ and $(k + 1)^{th}$ time step.

• At the tip of the binomial tree, the risky component $\tilde{S}$ is related to the asset price $S$ by

$$\tilde{S} = S - De^{-kr\Delta t}.$$

• The total value of asset price at the $(n, j)^{th}$ node, which corresponds to $n$ time steps from the tip and $j$ upward jumps, is given by

$$\tilde{S} u^j a^{n-j} + De^{-(k-n)r\Delta t} 1_{\{n \leq k\}},$$

where $n = 1, 2, \ldots, N$ and $j = 0, 1, \ldots, n$. 
A reconnecting binomial tree with single discrete dividend $D$

Here, $N = 4$ and $k = 2$, and let $\tilde{S}$ denote the risky component of the asset value at the tip of the binomial tree. The asset value at nodes $P$, $Q$ and $R$ are $\tilde{S} + De^{-2r\Delta t}$, $\tilde{S}u + De^{-r\Delta t}$ and $\tilde{S}d$, respectively.
Example 3

Consider a 5-month American put option on a stock that is expected to pay a single dividend of $2.06 during the life of the option. The initial stock price is $52, the strike price is $50, the risk-free interest rate is 10% per annum, the volatility is 40% per annum, and the ex-dividend date is in $3\frac{1}{2}$ months (which is 0.2917 years).

Solution

We construct a tree to model $\tilde{S}$ (risky component of the asset price process), the stock price less the present value of future dividends during the life of the option. At time zero, the present value of the dividend is

$$2.06e^{-0.2917 \times 0.1} = 2.00.$$
• The initial value of $\tilde{S}$ is therefore 50.00.

• Assuming that the 40% per annum volatility refers to $\tilde{S}$, the earlier figure on P.29 provides a binomial tree for $\tilde{S}$.

• Adding the present value of the dividend at each node leads to the figure on P.52, which is a binomial model for $\tilde{S}$.

• The probabilities at the nodes are 0.5073 for an up movement and 0.4927 for a down movement. Working back through the tree in the usual way gives the option price as 4.44.

Remark

Note that the exercise payoff is calculated using the actual asset price $S$, not the risky component $\tilde{S}$. 
At each node:

Upper value = Underlying Asset Price

Lower value = Option Price

Shading indicates where option is exercised

Strike price = 50

Discount factor per step = $1/R = 0.9917$

Time step, $\Delta t = 0.0833$ years, 30.42 days

Growth factor per step, $R = 1.0084$

Risk neutral probability of up move, $p = 0.5073$

Proportional up jump factor, $u = 1.1224$

Proportional down jump factor, $d = 1/u = 0.8909$
Tree when stock pays a known dividend yield at one particular time. The dividend amount is equal to \( \delta \) times the prevailing asset price. In this case, the interior nodes do recombine. Here, \( \delta \) is the dividend yield.
Pricing of lookback options

A path-dependent derivative is a derivative where the payoff depends on the path followed by the price of the underlying asset, not just its final value. Two important properties:

1. The payoff from the derivative must depend on a single function, \( F \), of the path followed by the underlying asset.

2. It must be possible to calculate the updated value of \( F \) at time \( t + \Delta t \) from the known value of \( F \) at time \( t \) and the updated value of the underlying asset at time \( t + \Delta t \).

For example, the realized maximum of a discrete asset price process over successive time steps is given by

\[
S_{i}^{\text{max}} = \max(S_{i-1}^{\text{max}}, S_{i}), \quad i = 2, 3, \ldots, n.
\]
American floating strike lookback put option on a non-dividend-paying stock (Hull-White, 1993)

- If the American floating strike lookback put option is exercised at time \( \tau \), the exercise payoff is the amount by which the maximum stock price between time 0 and time \( \tau \) exceeds the current stock price. That is,

\[
\max_{t \in [0, \tau]} S_t - S_{\tau}.
\]

Note that the strike in the put payoff is reset to a new value when a new maximum asset value is realized.

- We suppose that the initial stock price is $50, the stock price volatility is 40% per annum, the risk-free interest rate is 10% per annum, the total life of the option is three months, and that stock price movements are represented by a three-step binomial tree. That is, \( S_0 = 50, \sigma = 0.4, r = 0.10, \Delta t = 0.08333, u = 1.1224, d = 0.8909, R = 1.0084, \) and \( p = 0.5073 \).
Binomial tree for valuing an American lookback put option

Rolling back through the tree gives the value of the American lookback put as $5.47.
• The top number at each node is the stock price. The next level of numbers at each node shows the possible maximum stock prices achievable on all paths leading to the node. The bottom level of numbers show the values of the derivative corresponding to each of the possible maximum stock prices.

• The values of the derivatives at the final nodes of the tree are calculated as the maximum stock price minus the actual stock price.

• To illustrate the rollback procedures, suppose that we are at node A, where the stock price is $50. The maximum stock price achieved thus far is either 56.12 or 50 (depending on the path history of the asset price movement). Consider first where it is equal to 50. If there is an up movement, the maximum stock price becomes 56.12 and the value of the derivative is zero. If there is a down movement, the maximum stock price stays at 50 and the value of the derivative is 5.45.
• Assuming no early exercise, the value of the derivative at node $A$ when the maximum achieved so far is 50 is,

$$
(0 \times 0.5073 + 5.45 \times 0.4927)e^{-0.1 \times 0.08333} = 2.66.
$$

Clearly, it is not worth exercising at node $A$ because the payoff from doing so is zero.

• A similar calculation for the situation where the maximum value at node $A$ is 56.12 gives the value of the derivative at node $A$, without early exercise, to be

$$
(0 \times 0.5073 + 11.57 \times 0.4927)e^{-0.1 \times 0.08333} = 5.65.
$$

Early exercise gives a value of 6.12 and it is the optimal strategy.

• There may be multiple realized maximum asset values at each node. The different possible values of the path dependent function at a given node are linked to the corresponding path dependent function at the nodes that are one time step earlier.
There are 2 possible realized maximum at node $A$, one is 50.00 while the other is 56.12.

When the realized maximum at $A$ is 50.00, the realized maximum becomes 56.12 when the asset price moves up while the realized maximum remains at 50.00 when the asset price moves down.

When the realized maximum at $A$ is already 56.12, the realized maximum remains at 56.12 independent of whether the asset price moves up or down.
Alternative binomial algorithm (Cheuk-Vorst, 1997)

When the stock price $S_t$ is used as the numeraire, the payoff of the floating strike lookback put takes the form:

$$V_t = \frac{S_t^{\max}}{S_t} - 1,$$

where $S_t^{\max} = \max_{u \in [0,t]} S_u$.

We construct the truncated binomial tree for the process:

$$Y_t = \frac{S_t^{\max}}{S_t}, \quad Y_t \geq 1.$$

- At the tip of the binomial tree, $Y_0 = 1$.
- When $Y_t = 1$ where $S_t = S_t^{\max}$, then
  $$Y_{t+\Delta t} = \begin{cases} 
  u & \text{when } S_{t+\Delta t} = dS_t \\
  1 & \text{when } S_{t+\Delta t} = uS_t 
  \end{cases}.$$
- When $Y_t = u^j$ for some $j \geq 1$, then
  $$Y_{t+\Delta t} = \begin{cases} 
  u^{j+1} & \text{when } S_{t+\Delta t} = dS_t \\
  u^{j-1} & \text{when } S_{t+\Delta t} = uS_t 
  \end{cases}.$$
Let $\tilde{V}^n_j$ denote the numerical approximation to $\tilde{V}_t = V_t/S_t$ at the $(n, j)^{th}$ node of the binomial tree for $Y_t$, where $t = n\Delta t, n \geq 0$ and $Y_t = u^j, j \geq 0$.

From the risk neutral valuation principle, the lookback option values at successive time steps are related by

$$V^n_j = e^{-r\Delta t}[p\tilde{V}^{n+1}_{j-1} + (1-p)\tilde{V}^{n+1}_{j+1}], \quad j \geq 1.$$ 

Note that when the underlying $S_t$ jumps up from state $j$ to state $j + 1$ with probability $p$, $Y_t$ jumps down from state $j$ to state $j - 1$. In terms of $\tilde{V}^n_j$, we have

$$\tilde{V}^n_j S(t_n) = e^{-r\Delta t}[p\tilde{V}^{n+1}_{j-1} u S(t_n) + (1-p)\tilde{V}^{n+1}_{j+1} d S(t_n)],$$

so that

$$\tilde{V}^n_j = e^{-r\Delta t} [p\tilde{V}^{n+1}_{j-1} u + (1-p)\tilde{V}^{n+1}_{j+1} d].$$
• The continuation value is then given by

\[
\begin{cases}
    e^{-r\Delta t} \left[ (1 - p)\tilde{V}_{j+1}^{\max} + p\tilde{V}_{j-1}^{\max} \right], & j \geq 1 \\
    e^{-r\Delta t} \left[ (1 - p)\tilde{V}_{j+1}^{\max} + p\tilde{V}_{j-1}^{\max} \right], & j = 0
\end{cases}
\]

Note that when \( j = 0 \), the upward jump of \( S_t \) keeps \( Y_t \) to stay at the same value \( j = 0 \).

**Dynamic programming procedure for an American floating strike lookback option**

\[
\tilde{V}_j^n = \begin{cases}
    \max \left\{ Y_j - 1, e^{-r\Delta t} \left( (1 - p)\tilde{V}_{j+1}^{\max} + p\tilde{V}_{j-1}^{\max} \right) \right\}, & j \geq 1 \\
    \max \left\{ Y_j - 1, e^{-r\Delta t} \left( (1 - p)\tilde{V}_{j+1}^{\max} + p\tilde{V}_{j-1}^{\max} \right) \right\}, & j = 0
\end{cases}
\]

Dimension reduction is achieved by taking the stock price \( S(t_n) \) as the numeraire. The exercise payoff of the American floating strike lookback option can be expressed solely in terms of \( Y_j = \left( \frac{S_{t_j}^{\max}}{S_t} \right)_j \).
• The upper figures are values of $Y_t$ while the lower figures are option values at the nodes.

Cheuk-Vorst procedure for valuing an American-style lookback option. Though dimension reduction is achieved, the numerical scheme has very slow rate of convergence.
European floating strike currency lookback call ($S = 100$, $\tilde{r}_d = 0.04$, $\tilde{r}_f = 0.07$ and $T = 0.5$) with payoff: $S_T - \min_{[0, T]} S_{\tau}$.

<table>
<thead>
<tr>
<th>$N$</th>
<th>Option price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma = 0.1$</td>
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</tr>
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<tr>
<td>10000</td>
<td>4.65</td>
</tr>
<tr>
<td>Analytic</td>
<td>4.68</td>
</tr>
</tbody>
</table>

- The binomial results seem to converge very slowly to the analytical one (converge from below).

- The poor rate of convergence arises from the ineffective modeling of the recording of the newly realized maximum of the asset price (based on their intuitive derivation of the binomial formula at $j = 0$).
Binomial models for European fixed strike lookback call options

Terminal payoff = \( \max(\max_{0 \leq i \leq N} S(t_i) - K, 0) \).

Write \( \overline{M}(t_j) = \max_{0 \leq i \leq j} S(t_i) \) as the realized maximum asset value up to time \( t_j \), a known quantity at \( t_j \). Note that

\[
\max_{0 \leq i \leq N} S(t_i) = \max(\overline{M}(t_j), M(t_N; t_{j+1})),
\]

where \( M(t_N; t_{j+1}) = \max_{j+1 \leq i \leq N} S(t_i) \) is the random path dependent state variable for the future realized maximum asset value beyond time \( t_j \).

The fixed strike lookback call value can be expressed as

\[
c_{fix}(S(t_j), \overline{M}(t_j), t_j) = e^{-r(t_N-t_j)}E_Q[\max(\max(\overline{M}(t_j), M(t_N; t_{j+1})) - K, 0)].
\]
The terminal payoff can be decomposed into 2 terms:

\[
\max(\max(\overline{M}(t_j), M(t_N; t_{j+1})) - K, 0)
\]

\[
= \begin{cases} 
\max(M(t_N; t_{j+1}) - K, 0) & \text{if } \overline{M}(t_j) \leq K \\
\overline{M}(t_j) - K + \max(M(t_N; t_{j+1}) - \overline{M}(t_j), 0) & \text{if } \overline{M}(t_j) > K 
\end{cases}
\]

\[
= \max(\overline{M}(t_j) - K, 0) + \max(M(t_N; t_{j+1}) - \max(\overline{M}(t_j), K), 0).
\]

We observe that

- \( \overline{M}(t_j) \leq K \)
  \( \overline{M}(t_j) \) has no effect on the final option payoff.

- \( \overline{M}(t_j) > K \)
  Guaranteed to receive at least \( \overline{M}(t_j) - K \) at maturity, plus higher payoff if a higher realized maximum value is achieved at later time instants.

How to achieve dimension reduction?
Numerical procedure

Define the adjusted exercise price $K'$, where

$$K' = \max(M(t_j), K).$$

Assume that $K'$ is equal to $S_0u^m$ for some integer $m$, where $S_0$ is the initial asset price.

- If $K'$ is not the initial strike price, then this is always true since $M(t_j)$ is equal to $S_0u^m$ for some integer $m$.

- If otherwise, one may set the original strike price $K$ be equal to $S_0u^j$ for some integer $j$ (at least as a numerical approximation). In fact, it would not be quite a restriction if the number of time steps is sufficiently large.
Define

\[ k = \left( \ln \frac{S(t_j)}{K'} \right) / \ln u \Leftrightarrow K' = S(t_j)u^{-k}, \]

then \( k \) is always non-positive. This is because \( K' \geq \bar{M}(t_j) \geq S(t_j) \).

Once we have set \( K' = S_0u^j \) for some integer \( j \) and a similar form for \( S(t_j) \), we would like to check whether the fixed strike lookback call value \( c_X(S(t_j), K', t_j) \) is homogeneous in \( S(t_j) \). If so, homogeneity in \( S(t_j) \) helps achieve dimension reduction. Formally, we write

\[ X(k, t_j) = \frac{c_X(S(t_j), K', t_j)}{S(t_j)}. \]

We consider the separate scenarios where the next move in the asset price may or may not result in the updating of \( K' \). Note that if there is no updating of \( K' \), then \( k \) is increased (decreased) by one for an up-move (down-move) of the asset price.
• $k \leq -1 \ [S(t_j) \leq K'/u \text{ so that it is not possible to have an updated } K' \text{ in the next time step.}]

We adopt the usual backward induction procedure for the call value normalized by $S(t_j)$:

$$X(k, t_j) = [(1 - p)X(k - 1, t_{j+1})d + pX(k + 1, t_{j+1})u]e^{-r\Delta t}.$$  

The property of homogeneity in $S(t_j)$ is observed and implicitly adopted.

• $k = 0 \ [S(t_j) = K' = \max(M(t_j), K)]$

A downward move of the underlying asset price makes $k$ to become $-1$.

For an upward move, the underlying asset price exceeds the adjusted strike $K'$. The option holder is entitled to receive an extra payoff equal to $S(t_j)(u - 1)$ at maturity. Also, the value of $k$ remains to be zero with the updating value of $K' = S(t_{j+1})$ at $t_{j+1}$.
Conditional on an upward move, the present value of this extra payment is

\[ S(t_j)(u - 1)e^{-(N-j)r\Delta t}. \]

The guaranteed payoff \( M(t_j) - K \) arises from the accumulation of these payments. The corresponding binomial scheme is modified as

\[
X(0, t_j) = [(1 - p)X(-1, t_{j+1})d + pX(0, t_{j+1})u]e^{-r\Delta t} \\
+ p(u - 1)e^{-(N-j)r\Delta t}.
\]

**Terminal condition**

At maturity, the option value is zero since \( S(t_N) \leq K' = \max(M(t_N), K) \). We then have \( X(k, t_N) = 0 \) for all values of \( k \).

Though the option value is set to be zero at maturity under the present framework, we have been accumulating the sum of the present value of extra payments whenever a new updated \( K' \) is recorded.
• When $S(t_0) \geq K$, the fixed strike lookback call option is sure to be in-the-money. The truncated binomial tree starts at $(0, 0)$.

• When $S(t_0) < K$, we start the binomial tree at $(k, 0)$ with $k < 0$. 

\[
\begin{array}{cccc}
X(0,0) & \quad & X(0,1) & \quad & X(0,2) & \quad & X(0,3) \\
\quad & \downarrow & \quad & \times & \quad & \times & \quad & \times \\
X(-1,1) & \quad & X(-1,2) & \quad & X(-1,3) \\
\quad & \quad & \downarrow & \times & \quad & \times & \quad & \times \\
X(-2,2) & \quad & X(-2,3) & \quad & \times & \quad & \times & \quad & \times \\
\quad & \quad & \quad & \quad & \quad & \downarrow & \times & \quad & \times \\
X(-3,3)
\end{array}
\]
European fixed strike currency lookback call ($S = 100$, $K = 100$, $\tilde{r}_d = 0.04$, $\tilde{r}_f = 0.07$ and $T = 0.5$)

<table>
<thead>
<tr>
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<td></td>
<td>$\sigma = 0.1$</td>
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</tr>
<tr>
<td>Analytic</td>
<td>6.78</td>
</tr>
</tbody>
</table>

- The rate of convergence is very slow. Even with 10,000 time steps, the numerical results cannot achieve accuracy within 2% error.
Discretely monitored lookback options

$L$: number of observations
$z$: number of time steps between successive fixings

Let $t_i$, $i = 0, 1, ..., N$ be the set of discrete points;
$t_l$, $l = 0, z, ..., Lz$ be the observation points; where $Lz = N$.

Define the realized minimum asset value monitored at $l = 0, z, 2z, \ldots$, where $l \leq j$:

\[ M^z(t_j) = \min_{0 \leq iz \leq j} S(t_{iz}) \]

and

\[ k = \ln \frac{S(t_j)}{M^z(t_j)} / \ln u. \]

Note that $k$ assumes integer values that are larger than $-z$. 
Floating strike lookback call option

The call value \( c^z(S(t_j), M^z(t_j), t_j) \) also observes homogeneity in \( S(t_j) \), so we can write

\[
V^z(k, t_j) = \frac{c^z(S(t_j), M^z(t_j), t_j)}{S(t_j)}.
\]

This can be justified since \( S(t_j) \) and \( M^z(t_j) \) are expressible as \( S_0 u^l \) for some integer \( l \).

Take \( z = 3 \) as an illustrative example

At node \((-2, t_2)\), we have \( S(t_2) = \frac{M^3(t_2)}{u^2} \). With either an upward or a downward move of the underlying asset price, the new asset price will be below \( M^3(t_2) \). Hence, the new asset price at \( t_3 \) will become the new minimum \( M^3(t_3) \), so \( k = 0 \). This explains why node \((-2, 2)\) moves to node \((0, 3)\) for sure in the binomial tree. There is a subtree that emanates from the tip \((0, 3)\).
What is the interpretation of the double line joining $V^3(-2, 2)$ and $V^3(0, 3)$?

Floating strike currency lookback call, with $z = 3$.

The binomial tree may grow on the upside with the maximum value of $k$ equals the current time step $n$ but limited to $k = -(z - 1) < 0$ on the downside (due to updating of the realized minimum value).
When $t_{j+1} = iz$, we apply the following schemes:

(i) $k = 0,$

\[ V^z(0, t_{iz-1}) = [(1 - p)V^z(0, t_{iz})d + pV^z(1, t_{iz})u]e^{-r\Delta t}; \]

(ii) $k \leq -1,$

\[ V^z(k, t_{iz-1}) = [(1 - p)V^z(0, t_{iz})d + pV^z(0, t_{iz})u]e^{-r\Delta t} = V^z(0, t_{iz}). \]

When $t_{j+1} \neq iz$, we apply the usual binomial scheme:

\[ V^z(k, t_j) = [(1 - p)V^z(k - 1, t_{j+1})d + pV^z(k + 1, t_{j+1})u]e^{-r\Delta t}. \]
European floating strike currency lookback call, with different $L$ and $z$ ($S = 100$, $\tilde{r}_d = 0.04$, $\tilde{r}_f = 0.07$, $\sigma = 0.2$ and $T = 0.5$)

<table>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>6.14</td>
<td>4.65</td>
<td>4.76</td>
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<tr>
<td>2</td>
<td>6.45</td>
<td>5.72</td>
<td>5.82</td>
<td>5.83</td>
<td>5.83</td>
<td>5.84</td>
<td>5.84</td>
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<tr>
<td>6</td>
<td>7.65</td>
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<td>7.24</td>
<td>7.24</td>
<td>7.25</td>
<td>7.25</td>
<td>7.25</td>
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<tr>
<td>26</td>
<td>8.68</td>
<td>8.42</td>
<td>8.46</td>
<td>8.47</td>
<td>8.47</td>
<td>8.47</td>
<td>8.48</td>
<td>8.48</td>
</tr>
</tbody>
</table>

- The option values shown in the columns indicate that the lookback call value increases with the number of observation points (substantial price difference between daily and weekly fixing options).

- The option values shown in rows converge quite well. For example, with $z = 100$, the option values (for fixed value of $L$) are already quite accurate. The Cheuk-Vorst algorithm performs quite well for pricing discretely monitored lookback options.
Research papers on numerical methods on lookback options


Cheuk-Vorst's algorithm suffers from an extremely slow rate of convergence when compared to other schemes for pricing continuously monitored lookback options.

### Comparison of the Numerical Accuracy of the Lookback Option Values Obtained from the Lax–Wendroff Scheme, Cheuk–Vorst Scheme, and Babbs Scheme

<table>
<thead>
<tr>
<th>Volatility</th>
<th>Numerical Schemes</th>
<th>Number of Time Steps</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>100</td>
<td>500</td>
<td>1000</td>
<td>10,000</td>
</tr>
<tr>
<td>$\sigma = 0.1$</td>
<td>LW scheme</td>
<td>4.6691</td>
<td>4.6745</td>
<td>4.6789</td>
<td>4.6794</td>
<td>4.6799</td>
</tr>
<tr>
<td></td>
<td>CV scheme</td>
<td>4.24</td>
<td>4.37</td>
<td>4.54</td>
<td>4.58</td>
<td>4.65</td>
</tr>
<tr>
<td>$\sigma = 0.2$</td>
<td>LW scheme</td>
<td>9.7415</td>
<td>9.7673</td>
<td>9.7870</td>
<td>9.7891</td>
<td>9.7912</td>
</tr>
<tr>
<td></td>
<td>CV scheme</td>
<td>8.97</td>
<td>9.20</td>
<td>9.52</td>
<td>9.60</td>
<td>9.73</td>
</tr>
<tr>
<td>$\sigma = 0.3$</td>
<td>LW scheme</td>
<td>14.5964</td>
<td>14.6419</td>
<td>14.6785</td>
<td>14.6826</td>
<td>14.6868</td>
</tr>
</tbody>
</table>

The parameter values of the continuously monitored European floating strike lookback call option are: $S = m T_0 = 100$, $r = 0.04$, $q = 0.07$, and $\tau = 0.5$. 

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1.2 Trinomial schemes

In a trinomial model, the asset price $S$ is assumed to jump to either $uS$, $mS$ or $dS$ after one time period $\Delta t$, where $u > m > d$. We consider a trinomial formula of option valuation of the form

$$V = \frac{p_1 V_u \Delta t + p_2 V_m \Delta t + p_3 V_d \Delta t}{R}, \quad R = e^{r \Delta t}.$$ 

This is deduced from the risk neutral valuation principle: the current option value is the discounted expectation of the terminal option value under the risk neutral pricing measure.

There are 6 unknowns: $p_1, p_2, p_3, u, m$ and $d$. We take $m = 1, u = 1/d$. We obtain 3 equations by

(i) equating mean,  (ii) equating variance,

(iii) setting sum of probabilities = 1. We are left with one free parameter.
Discounted expectation approach

Under the assumption of the Geometric Brownian process followed by the continuous asset price process, we write

\[ \ln S_{t+\Delta t} = \ln S_t + \zeta, \]

where \( \zeta \) is a normal random variable with mean \( \left( r - \frac{\sigma^2}{2} \right) \Delta t \) and variance \( \sigma^2 \Delta t \). We approximate \( \zeta \) by an approximate discrete random variable \( \zeta^a \) with the following distribution

\[ \zeta^a = \begin{cases} 
  v & \text{with probability } p_1 \\
  0 & \text{with probability } p_2 \\
  -v & \text{with probability } p_3 
\end{cases} \]

where \( v = \lambda \sigma \sqrt{\Delta t} \) and \( \lambda \geq 1 \). The corresponding values for \( u, m \) and \( d \) in the trinomial scheme are: \( u = e^v, m = 1 \) and \( d = e^{-v} \). This is because when \( \ln \frac{S_{t+\Delta t}}{S_t} \) assumes the value \( v \), then \( \frac{S_{t+\Delta t}}{S_t} \) assumes the value \( e^v \).
To find the probability values $p_1, p_2$ and $p_3$, the mean and variance of the approximating discrete trinomial random walk variable $\zeta^a$ are chosen to be equal to those of $\zeta$. These lead to

$$E[\zeta^a] = v(p_1 - p_3) = \left(r - \frac{\sigma^2}{2}\right) \Delta t$$

$$\text{var}(\zeta^a) = v^2(p_1 + p_3) - v^2(p_1 - p_3)^2 = \sigma^2 \Delta t.$$ 

We see that $v^2(p_1 - p_3)^2 = O(\Delta t^2)$. We may drop this term so that

$$v^2(p_1 + p_3) = \sigma^2 \Delta t,$$

while still maintaining $O(\Delta t)$ accuracy.

By considering the approximation of $\ln \frac{S_{t+\Delta t}}{S_t}$ instead of $\frac{S_{t+\Delta t}}{S_t}$, the algebraic equations for solving $p_1, p_2$ and $p_3$ involve only linear functions of $\Delta t$ rather than exponential functions of $\Delta t$. 
Lastly, the probabilities must be summed to one so that

\[ p_1 + p_2 + p_3 = 1. \]

We then solve together to obtain

\[
\begin{align*}
p_1 &= \frac{1}{2\lambda^2} + \frac{(r - \frac{\sigma^2}{2})\sqrt{\Delta t}}{2\lambda \sigma} \\
p_2 &= 1 - \frac{1}{\lambda^2} \\
p_3 &= \frac{1}{2\lambda^2} - \frac{(r - \frac{\sigma^2}{2})\sqrt{\Delta t}}{2\lambda \sigma},
\end{align*}
\]

here \( \lambda \) is a free parameter.

- In order that \( p_2 \geq 0 \), we must choose \( \lambda \geq 1 \).

- Numerical experiments indicate that the optimal choice of \( \lambda \) is \( \sqrt{3} \) so that \( p_2 = 2/3 \).
• Note that $p_2 = 0$ when $\lambda = 1$, which reduces to the Cox-Ross-Rubinstein binomial scheme. This illustrates an effective mean of deriving the binomial/trinomial parameters using the discrete approximation of the logarithm of the price ratio at successive time steps.

• When $\lambda = 1$, $p_1 = \frac{1}{2} + \frac{(r - \sigma^2/2)^2}{2\sigma} \sqrt{\Delta t}$. This would agree with the Taylor expansion of $p = \frac{R - d}{u - d}$, $u = 1/d = e^{\sigma \sqrt{\Delta t}}$ up to $O(\Delta t)$. 
Multistate extension – Kamrad-Ritchken’s approach

- We assume the joint density of the prices of the two underlying assets $S_1$ and $S_2$ to be bivariate lognormal.
- Let $\sigma_i$ be the volatility of asset price $S_i$, $i = 1, 2$ and $\rho$ be the correlation coefficient between the two lognormal diffusion processes.
- Let $S_i$ and $S_i^{\Delta t}$ denote, respectively, the price of asset $i$ at the current time and one period $\Delta t$ later.
- Under the risk neutral measure, we have

$$\ln \frac{S_i^{\Delta t}}{S_i} = \zeta_i, \quad i = 1, 2,$$

where $\zeta_i$ is a normal random variable with mean $\left( r - \frac{\sigma_i^2}{2} \right) \Delta t$ and variance $\sigma_i^2 \Delta t$. 
The instantaneous correlation coefficient between $\zeta_1$ and $\zeta_2$ is $\rho$. The joint bivariate normal process $\{\zeta_1, \zeta_2\}$ is approximated by a pair of joint discrete random variables $\{\zeta^a_1, \zeta^a_2\}$ with the following distribution

<table>
<thead>
<tr>
<th>$\zeta^a_1$</th>
<th>$\zeta^a_2$</th>
<th>probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_1$</td>
<td>$v_2$</td>
<td>$p_1$</td>
</tr>
<tr>
<td>$v_1$</td>
<td>$-v_2$</td>
<td>$p_2$</td>
</tr>
<tr>
<td>$-v_1$</td>
<td>$-v_2$</td>
<td>$p_3$</td>
</tr>
<tr>
<td>$-v_1$</td>
<td>$v_2$</td>
<td>$p_4$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>$p_5$</td>
</tr>
</tbody>
</table>

where $v_i = \lambda_i \sigma_i \sqrt{\Delta t}$, $i = 1, 2$.

The above form of the discrete distribution can be shown to be sufficient to serve as the discrete approximation of the correlated diffusion processes with drifts. It is redundant to include scenarios, like $\zeta^a_1 = v_1$ and $\zeta^a_2 = 0$, etc.
Equating the corresponding means gives

\[ E[\zeta^a_1] = v_1(p_1 + p_2 - p_3 - p_4) = \left( r - \frac{\sigma_1^2}{2} \right) \Delta t \]  

(i)

\[ E[\zeta^a_2] = v_2(p_1 - p_2 - p_3 + p_4) = \left( r - \frac{\sigma_2^2}{2} \right) \Delta t. \]  

(ii)

By equating the variances and covariance to \( O(\Delta t) \) accuracy, we have

\[ \text{var}(\zeta^a_1) = v_1^2(p_1 + p_2 + p_3 + p_4) = \sigma_1^2 \Delta t \]  

(iii)

\[ \text{var}(\zeta^a_2) = v_2^2(p_1 + p_2 + p_3 + p_4) = \sigma_2^2 \Delta t \]  

(iv)

\[ E[\zeta^a_1 \zeta^a_2] = v_1 v_2(p_1 - p_2 + p_3 - p_4) = \sigma_1 \sigma_2 \rho \Delta t. \]  

(v)

In order that Eqs. (iii) and (iv) are consistent, we must set \( \lambda_1 = \lambda_2 \).
Writing $\lambda = \lambda_1 = \lambda_2$, we have the following four independent equations for the five probability values

\[
p_1 + p_2 - p_3 - p_4 = \frac{(r - \frac{\sigma_1^2}{2})\sqrt{\Delta t}}{\lambda \sigma_1}
\]

\[
p_1 - p_2 - p_3 + p_4 = \frac{(r - \frac{\sigma_2^2}{2})\sqrt{\Delta t}}{\lambda \sigma_2}
\]

\[
p_1 + p_2 + p_3 + p_4 = \frac{1}{\lambda^2}
\]

\[
p_1 - p_2 + p_3 - p_4 = \frac{\rho}{\lambda^2}.
\]

Since the probabilities must be summed to one, this gives the remaining condition as

\[
p_1 + p_2 + p_3 + p_4 + p_5 = 1.
\]
The solution of the above linear algebraic system of equations gives

\[ p_1 = \frac{1}{4} \left[ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( \frac{r - \sigma_1^2}{2} + \frac{r - \sigma_2^2}{2} \right) + \frac{\rho}{\lambda^2} \right] \]

\[ p_2 = \frac{1}{4} \left[ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( \frac{r - \sigma_1^2}{2} - \frac{r - \sigma_2^2}{2} \right) - \frac{\rho}{\lambda^2} \right] \]

\[ p_3 = \frac{1}{4} \left[ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( -\frac{r - \sigma_1^2}{2} - \frac{r - \sigma_2^2}{2} \right) + \frac{\rho}{\lambda^2} \right] \]

\[ p_4 = \frac{1}{4} \left[ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( -\frac{r - \sigma_1^2}{2} + \frac{r - \sigma_2^2}{2} \right) - \frac{\rho}{\lambda^2} \right] \]

\[ p_5 = 1 - \frac{1}{\lambda^2}, \quad \lambda \geq 1 \text{ is a free parameter.} \]
Two-state trinomial model

- For convenience, we write $u_i = e^{v_i}$, $d_i = e^{-v_i}$, $i = 1, 2$.
- Let $V_{u_1u_2}^{\Delta t}$ denote the option price at one time period later with asset prices $u_1 S_1$ and $u_2 S_2$, and similar meaning for $V_{u_1d_2}^{\Delta t}$, $V_{d_1u_2}^{\Delta t}$, and $V_{d_1d_2}^{\Delta t}$.
- We let $V_{0,0}^{\Delta t}$ denote the option price one period later with no jumps in asset prices.
- The corresponding 5-point formula for the two-state trinomial model based on the risk neutral valuation approach can be expressed as
  \[ V = \left( p_1 V_{u_1u_2}^{\Delta t} + p_2 V_{u_1d_2}^{\Delta t} + p_3 V_{d_1d_2}^{\Delta t} + p_4 V_{d_1u_2}^{\Delta t} + p_5 V_{0,0}^{\Delta t} \right) / R. \]
- When $\lambda = 1$, we have $p_5 = 0$ and the above 5-point formula reduces to the 4-point formula.
1.3 Forward shooting grid methods (strongly path dependent options)

- For path dependent options, the option value also depends on the path function \( F_t = F(S,t) \) defined specifically for the given nature of path dependence, say, the minimum asset price realized along a specific asset price path.

- Since option value depends also on \( F_t \), we find the value of the path dependent option at each node in the lattice tree for all alternative values of \( F_t \) that can occur.

- The approach of appending an auxiliary state vector at each node in the lattice tree to model the correlated evolution of \( F_t \) with \( S_t \) is commonly called the *forward shooting grid (FSG) method*. 

• Consider a trinomial tree whose probabilities of upward, zero and downward jump of the asset price are denoted by $p_u$, $p_0$ and $p_d$, respectively.

• Let $V_{n,j,k}^n$ denote the numerical option value of the exotic path dependent option at the $n^{\text{th}}$-time level ($n$ time steps from the tip of the tree). Also, $j$ denotes the $j$ upward jumps from the initial asset value and $k$ denotes the numbering index for the various possible values of the augmented state variable $F_t$ at the $(n,j)^{\text{th}}$ node.

• Let $G$ denote the function that describes the correlated evolution of $F_t$ with $S_t$ over the time interval $\Delta t$, that is,

$$F_{t+\Delta t} = G(t, F_t, S_{t+\Delta t}).$$
• Let \( g(k, n, j) \) denote the grid function which is considered as the discrete analog of the evolution function \( G \).

• The trinomial version of the FSG scheme can be represented as follows

\[
V^n_{j,k} = \left[ p_u V^{n+1}_{j+1,k, n+1} + p_0 V^{n+1}_{j,k, n} + p_d V^{n+1}_{j-1,k, n-1} \right] e^{-r \Delta t},
\]

where \( e^{-r \Delta t} \) is the discount factor over time interval \( \Delta t \).

• To price a specific path dependent option, the design of the FSG algorithm requires the specification of the grid function \( g(k, n, j) \).

For notational convenience, if the grid function has no dependence on \( t \), we simply write it as \( g(k, j) \).
Cumulative Parisian feature of knock-out

• Let $M$ denote the prespecified number of cumulative breaching occurrences that is required to activate knock-out, and let $k$ be the integer variable that counts the cumulative number of breaching occurrences so far.

• Let $B$ denote the down barrier associated with the knock-out feature. Let $x_j$ denote the value of $x = \ln S$ that corresponds to $j$ upward moves in the trinomial tree. That is, $x_j = \ln S_0 + j\Delta x$, where $S_0$ is the initial asset price and $\Delta x$ is the stepwidth of the state variable $x$.

• When $n\Delta t$ happens to be a monitoring instant, the index $k$ increases its value by 1 if the asset price $S$ falls on or below the barrier $B$, that is, $x_j \leq \ln B$. 
**Counting the number of time steps that** $x_j$ **falls below or at** $\ln B$

To incorporate the cumulative Parisian feature, the appropriate choice of the grid function $g_{cum}(k, j)$ is defined by

$$g_{cum}(k, j) = k + 1_{\{x_j \leq \ln B\}}.$$

The backward induction procedure in the trinomial tree calculations is exemplified by

$$V_{n-1}^{j,k} = \begin{cases} 
[p_u V_{j+1,k}^{n-1} + p_0 V_{j,k}^{n} + p_d V_{j-1,k}^{n}]e^{-r\Delta t} & \text{if } n\Delta t \text{ is not a monitoring instant} \\
[p_u V_{j+1,g_{cum}(k,j+1)}^{n-1} + p_0 V_{j,g_{cum}(k,j)}^{n} + p_d V_{j-1,g_{cum}(k,j-1)}^{n}]e^{-r\Delta t} & \text{if } n\Delta t \text{ is a monitoring instant}
\end{cases}$$

The number of breaching occurrences $k$ is updated to $g_{cum}(k, j + 1)$ when the updated asset price at the $n^{th}$ time level is $S_{j+1}^{n}$ [up move from $S_{j}^{n-1}$ at the $(n - 1)^{th}$ time level]. The knock-out condition is defined by $V_{j,M}^{n} = 0$. 

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Schematic diagram that illustrates the construction of the grid function $g_{cum}(k, j)$ that models the cumulative Parisian feature. The down barrier $\ln B$ is placed mid-way between two horizontal rows of trinomial nodes. Here, the $n^{th}$-time level is a monitoring instant. In this example, the backward induction procedure is

$$V_{j,k}^{n-1} = \left[p_u V_{j+1,k}^n + p_0 V_{j,k}^n + p_d V_{j-1,k+1}^n\right] e^{-r\Delta t}, \quad k = 1, 2, \ldots.$$
1. The pricing of options with the continuously monitored cumulative Parisian feature is obtained by setting all time steps to be monitoring instants.

2. The computational time required for pricing an option with the cumulative Parisian feature requiring $M$ breaching occurrences to knock out is about $M$ times that of an one-touch knock-out barrier option.

3. The size of the augmented state vector appended at each node grows from zero at the tip of the trinomial tree to the maximum size of $M$ as we proceed the time marching in the trinomial calculations.

Reference (improvement on computational complexity)
4. Applications of the cumulative counting feature can also be found in structured products, say, the coupons (as in reverse convertibles) are accrued contingent on the underlying stock price lying within certain range of values.

5. The *consecutive Parisian feature* counts the number of consecutive breaching occurrences that the asset price stays in the knock-out region. The count is reset to zero once the asset price moves out from the knock-out region. Assuming $B$ to be the down barrier, the appropriate grid function $g_{\text{con}}(k, j)$ in the FSG algorithm is given by

$$g_{\text{con}}(k, j) = (k + 1) \mathbf{1}_{\{x_j \leq \ln B\}}.$$

6. The consecutive counting feature can be found in the soft call provision in a convertible bond. In most convertible bond contracts, the issuer is allowed to issue the notice of redemption conditional on the underlying stock price staying above the preset hurdle price for a prespecified number of trading days.
Call options with the strike reset feature

- Consider a call option with the strike reset feature where the option’s strike price is reset to the prevailing asset price on a preset reset date if the option is out-of-money on that date.

- Let \( t_i, i = 1, 2, \ldots, M \), denote the \( i^{th} \) reset date and \( X_i \) denote the strike price specified on \( t_i \) based on the above reset rule.

- Write \( X_0 \) as the strike price set at initiation, then \( X_i \) is given by

\[
X_i = \min(X_{i-1}, S_{t_i}), \quad i = 1, 2, \ldots, M,
\]

where \( S_{t_i} \) is the prevailing asset price on the reset date \( t_i \).

- Why does it become superfluous to set

\[
X_i = \min(X_{i-1}, S_{t_i}, X_0), \quad i = 1, 2, \ldots, M?
\]

Since \( X_1 = \min(X_0, S_{t_1}) \), the information of the initial strike price \( X_0 \) has been embedded in the strike reset procedure.
• The strike price at expiry of this call option is not fixed since its value depends on the realization of the asset price on the reset dates.

• When we apply the backward induction procedure in the trinomial calculations, we encounter the difficulty in defining the terminal payoff since the strike price can assume many possible values due to the reset mechanism.

• These difficulties can be resolved easily using the FSG approach by tracking the evolution of the asset price and the strike reset through an appropriate choice of the grid function. The terminal payoff in the FSG lattice tree is computed with respect to all possible values of $k$ that can be realized at maturity.

Remark If we do not impose the initial strike $X_0$, then this strike reset call option resembles the discretely monitored floating strike lookback call option with terminal payoff: \( \max(S_T - S_{\text{min}}, 0) \).
Suppose the original strike price $X_0$ corresponds to the index $k_0$, this would mean $X_0 = S_0 u^{k_0}$. For convenience, we may choose the proportional jump parameter $u$ such that $k_0$ is an integer. In terms of these indexes, the grid function that models the correlated evolution between the reset strike price and asset price is given by

$$g_{\text{reset}}(k, j) = \min(k, j),$$

where $k$ denotes the index that corresponds to the strike price reset in the last reset date and $j$ is the index that corresponds to the prevailing asset price at the reset date.

Since the strike price is reset only on a reset date, we perform the usual trinomial calculations for those time levels that do not correspond to a reset date while the augmented state vector of strike prices are adjusted according to the grid function $g_{\text{reset}}(k, j)$ for those time levels that correspond to a reset date.
• The FSG algorithm for pricing the reset call option is given by

\[
V_{n-1}^{j,k} = \begin{cases} 
\left[ p_u V_{j+1,k}^n + p_0 V_{j,k}^n + p_d V_{j-1,k}^n \right] e^{-r \Delta t} 
\quad & \text{if } n \Delta t \neq t_i \text{ for some } i \\
\left[ p_u V_{j+1,\text{reset}(k,j+1)}^n + p_0 V_{j,\text{reset}(k,j)}^n + p_d V_{j-1,\text{reset}(k,j-1)}^n \right] e^{-r \Delta t}, 
\quad & \text{if } n \Delta t = t_i \text{ for some } i 
\end{cases}
\]

• The payoff values along the terminal nodes at the \( N \)th time level in the trinomial tree are given by

\[
V_{j,k}^N = \max(S_0 u^j - S_0 u^k, 0), \quad j = -N, -N + 1, \ldots, N,
\]

and \( k \) assumes values that lie between \( k_0 \) and the index corresponding to the lowest asset price on the last reset date.
Floating strike arithmetic averaging call

- To price an Asian option, we find the option value at each node for all possible values of the path function $F(S, t)$ that can occur at that node.

- Unfortunately, the number of possible values for the averaging value $F$ at a binomial node for the arithmetic averaging option grows exponentially at $2^n$, where $n$ is the number of time steps from the tip of the binomial tree. (Why $2^n$? Since there are $2^n$ possible realized asset paths after $n$ time steps and each path gives a unique arithmetic averaging value.)

- Therefore, the binomial schemes that place no constraint on the number of possible $F$ values at the binomial nodes would become computationally infeasible.
Illustration

Consider the following tree

There are $4 = 2^2$ possible arithmetic averaging values after 2 time steps, namely,

\[
A_{uu} = \frac{50.00 + 56.12 + 62.99}{3}, \quad A_{ud} = \frac{50.00 + 56.12 + 50.00}{3},
\]

\[
A_{du} = \frac{50.00 + 44.55 + 50.00}{3}, \quad A_{dd} = \frac{50.00 + 44.55 + 39.69}{3}.
\]
Note that these arithmetic averaging values do not coincide with the stock prices at the nodes at the 2^{nd} time level. Extending to a 3-step binomial tree, there are $8 = 2^3$ possible arithmetic averaging values, namely, $A_{uuu}, A_{uud}, A_{udu}, \ldots, A_{ddd}$.

**Geometric averaging values**

- **Two-step binomial tree**
  
  \[
  G_{uu} = \sqrt[3]{(S_0)(S_0u)(S_0u^2)} = S_0u,
  \]
  
  \[
  G_{dd} = \sqrt[3]{S_0(S_0u^{-1})(S_0u^{-2})} = S_0u^{-1},
  \]
  
  \[
  G_{ud} = \sqrt[3]{(S_0)(S_0u)(S_0)} = S_0u^{1/3},
  \]
  
  \[
  G_{du} = \sqrt[3]{(S_0)(S_0u^{-1})(S_0)} = S_0u^{-1/3}.
  \]

Some of these 4 geometric averaging values may coincide with the stock prices at the nodes at the 2^{nd} time level.
• Three-step binomial tree

\[ G_{uuu} = \sqrt[4]{(S_0)(S_0u)(S_0u^2)(S_0u^3)} = S_0u^{1.5}, \]
\[ G_{ddd} = \sqrt[4]{(S_0)(S_0u^{-1})(S_0u^{-2})(S_0u^{-3})} = S_0u^{-1.5}, \]
\[ G_{uud} = \sqrt[4]{(S_0)(S_0u)(S_0u^2)(S_0u)} = S_0u, \]
\[ G_{udu} = S_0u^{0.5}, \quad G_{duu} = S_0u^{0.25}, \]
\[ G_{udd} = \sqrt[4]{(S_0)(S_0u)(S_0)(S_0u^{-1})} = S_0, \]
\[ G_{dud} = S_0u^{-0.5}, \quad G_{ddu} = S_0u^{-1}. \]

There are 8 possible geometric averaging values after 3 time steps. In general, we have \(2^n\) geometric averaging values after \(n\) time steps.
• A possible remedy is to restrict the possible values for $F$ to a certain set of predetermined values. The option value $V(S, F, t)$ for other values of $F$ is obtained from the known values of $V$ at predetermined $F$ values by an interpolation between the nodal values.

• The methods of interpolation include the nearest node interpolation, linear (between 2 neighboring nodes) and quadratic interpolation (between 3 neighboring nodes).

• How to cope with the exponentially large number of possible values assumed by taking the arithmetic averaging of the realized asset price path? We limit the number of averaging values to some multiple of the number of values assumed by the asset price (here, the multiple is $1/\rho$).
For a given time step $\Delta t$, we fix the stepwidths to be

$$\Delta W = \sigma \sqrt{\Delta t} \quad \text{and} \quad \Delta Y = \rho \Delta W, \quad \rho < 1,$$

and define the possible values for $S_t$ and $A_t$ at the $n^{th}$ time step by

$$S^n_j = S_0 e^{j \Delta W} \quad \text{and} \quad A^n_k = S_0 e^{k \Delta Y},$$

where $j$ and $k$ are integers, and $S_0$ is the asset price at the tip of the binomial tree.

- We take $1/\rho$ to be an integer. The larger integer value chosen for $1/\rho$, the finer the quantification of the arithmetic averaging asset value.
Quantification of arithmetic averaging asset value \( \left( \text{Here, } \frac{1}{\rho} = 3 \text{ is taken.} \right) \)

After 2 time steps

- \( S_0 e^{2\Delta w} \)
- \( S_0 e^{\Delta w} \)
- \( S_0 \)
- \( S_0 e^{-\Delta w} \)
- \( S_0 e^{-2\Delta w} \)

Stock price

After 2 time steps

- \( A_0 e^{6\Delta y} \)
- \( A_0 e^{3\Delta y} \)
- \( A_0 \)
- \( A_0 e^{-3\Delta y} \)
- \( A_0 e^{-6\Delta y} \)

Averaging price
The continuous version of the arithmetic averaging state variable is defined by

\[ A_t = \frac{1}{t} \int_0^t S_u \, du. \]

- The terminal payoff of the floating strike Asian call option is given by \( \max(S_T - A_T, 0) \), where \( A_T \) is the arithmetic average of \( S_t \) over the time period \([0, T]\).

- Similarly, the terminal payoffs of other related Asian options are
  
  (i) Floating strike Asian put option: \( \max(A_T - S_T, 0) \);
  (ii) Fixed strike Asian call option: \( \max(A_T - X, 0) \), where \( X \) is the fixed strike price.
**Updating rule of $A_t$ over successive discrete time points**

Consider the following relation between $A_t$ and $S_t$ in differential form:

$$d(tA_t) = S_t \, dt \text{ or } dA_t = \frac{1}{t}(S_t - A_t) \, dt,$$

we approximate the above differential at time $t + \Delta t$ by adopting \((t + \Delta t)[A_{t+\Delta t} - A_t] = (S_{t+\Delta t} - A_{t+\Delta t})\Delta t\), so that

$$A_{t+\Delta t} = \frac{(t + \Delta t)A_t + \Delta t \, S_{t+\Delta t}}{t + 2\Delta t} \equiv G(t, A_t, S_{t+\Delta t}).$$

This is the updating rule of $A_{t+\Delta t} \Delta t$ at the new time level $t + \Delta t$ based on the old value $A_t$ at the previous time level $t$ and the updated asset value $S_{t+\Delta t}$ at the new time level $t + \Delta t$.

Alternatively, given the discrete asset values $S(t_0), S(t_1), \ldots, S(t_n)$, the discrete geometric average $G(t_n)$ is given by

$$\ln G(t_n) = \frac{1}{n + 1}[\ln S(t_0) + \ln S(t_1) + \cdots + \ln S(t_n)].$$

It is straightforward to find $G(t_{n+1})$ based on the arrival of $S(t_{n+1})$. 
Consider the binomial procedure at the \((n, j)\)th node, suppose we have an upward move in the asset price from \(S^n_j\) to \(S^{n+1}_{j+1}\) and let \(A^{n+1}_{k^+(j)}\) be the corresponding updated value of \(A_t\) changing from \(A^n_k\) when the asset price moves up from \(S^n_j\) to \(S^{n+1}_{j+1}\). Setting \(A^0_0 = S_0\) and taking \(t = n\Delta t\), the equivalence of the above discrete updating rule is given by

\[
A^{n+1}_{k^+(j)} = \frac{(n + 1)A^n_k + S^{n+1}_{j+1}}{n + 2}. \tag{a}
\]

For a downward move in asset price from \(S^n_j\) to \(S^{n+1}_{j-1}\), \(A^n_k\) changes to \(A^{n+1}_{k^-(j)}\) where

\[
A^{n+1}_{k^-(j)} = \frac{(n + 1)A^n_k + S^{n+1}_{j-1}}{n + 2}. \tag{b}
\]

Note that \(A^{n+1}_{k^\pm(j)}\) in general do not coincide with \(A^{n+1}_{k'} = S_0 e^{k'\Delta Y}\), for some integer \(k'\).
In terms of $\Delta W$ and $\Delta Y$, eqs. (a) and (b) can be expressed as

$$e^{k^\pm(j)}\Delta Y = \frac{(n + 1)e^k\Delta Y + e^{(j\pm1)}\Delta W}{n + 2}.$$ 

Accordingly, we compute the indexes $k^\pm(j)$ by

$$g(n, k, j \pm 1) = k^\pm(j) = \frac{\ln (n+1)e^k\Delta Y + e^{(j\pm1)}\Delta W}{n+2} \Delta Y.$$ 

(1)

- We define the integers $k^\pm_{\text{floor}}$ such that $A_{k^\pm_{\text{floor}}}^{n+1}$ are the largest possible $A_{k'}^{n+1}$ values less than or equal to $A_k^{n+1}$. We then set $k^+_{\text{floor}} = \text{floor}(k^+(j))$ and $k^-_{\text{floor}} = \text{floor}(k^-(j))$, where $\text{floor}(x)$ denotes the largest integer less than or equal to $x$. Equation (1) corresponds to the evolution of $A_k^n$ to $A_{k^\pm(j)}^n$ depending on the updated value of $S_{j\pm1}^{n+1}$ [in terms of the indexes $k$ and $k^\pm(j)$].
Restricting the size of the augmented state vector representing possible averaging values

- What would be the possible range of $k$ at the $n^{th}$ time step? We observe that the arithmetic averaging state variable $A_t$ must lie between the maximum asset value $S^n$ and the minimum asset value $S^n_{-n}$, so $k$ must lie between $-\frac{n}{\rho} \leq k \leq \frac{n}{\rho}$. Unless $\rho$ assumes a very small value, the number of predetermined values for $A_t$ is in general manageable.

- Consider $A^n_\ell$, where $\ell$ is in general a real number. We write $\ell_{\text{floor}} = \text{floor}(\ell)$ and let $\ell_{\text{ceil}} = \ell_{\text{floor}} + 1$, then $A^n_\ell$ lies between $A^n_{\ell_{\text{floor}}}$ and $A^n_{\ell_{\text{ceil}}}$. Though the number of possible values of $\ell$ grows exponentially with the number of time steps in the binomial tree, both $\ell_{\text{floor}}$ and $\ell_{\text{ceil}}$ at the $n^{th}$ time level assume an integer value lying between $-\frac{n}{\rho}$ and $\frac{n}{\rho}$. 
Linear interpolation

- Let $c_{j,\ell}^n$ denote the numerical approximation to the Asian call value at the $(n, j)^{th}$ node with the averaging state variable assuming the value $A_n^\ell$, and similar notations for $c_{j,\ell_{floor}}^n$ and $c_{j,\ell_{ceil}}^n$.

- For non-integer value $\ell$, $c_{j,\ell}^n$ is approximated through linear interpolation using the call values $c_{j,\ell_{floor}}^n$ and $c_{j,\ell_{ceil}}^n$ at the neighboring nodes.

$$c_{j,\ell}^n = \epsilon_\ell c_{j,\ell_{ceil}}^n + (1 - \epsilon_\ell)c_{j,\ell_{floor}}^n,$$

where

$$\epsilon_\ell = \frac{\ln A_n^\ell - \ln A_{\ell_{floor}}^n}{\Delta Y}.$$ 

Here, $\epsilon_\ell$ is the fraction of one time step that lies between $\ell_{floor}$ and $\ell_{ceil}$, where

$$A_n^\ell = A_{\ell_{floor}}^n e^{\epsilon_\ell \Delta Y}.$$
• Here, $\ell$ is a real number lying between two consecutive integers $\text{floor}(\ell)$ and $\text{ceil}(\ell)$, where $\text{ceil}(\ell) = \text{floor}(\ell) + 1$.

• Numerical option values are available only at $A_{\text{floor}(\ell)}^n$ and $A_{\text{ceil}(\ell)}^n$, where the index $k$ in $A_k^n$ assumes an integer value [like floor$(\ell)$ or ceil$(\ell)$].

• For $\ell$ to be non-integer, we approximate $c_{j,\ell}^n$ by linear interpolation between $c_{j,\text{floor}(\ell)}^n$ and $c_{j,\text{ceil}(\ell)}^n$. 
By applying the above linear interpolation formula [taking $\ell$ to be $k^+(j)$ and $k^-(j)$ successively], the FSG algorithm with linear interpolation for pricing the floating strike arithmetic averaging call option is given by

$$c_{n,j,k} = e^{-r\Delta t} \left[ p c_{n+1,j+1,k^+(j)} + (1 - p) c_{n+1,j-1,k^-(j)} \right]$$

$$= e^{-r\Delta t} \left\{ p \left[ \epsilon_{k^+(j)} c_{n+1,j+1,k^+_{ceil}} + (1 - \epsilon_{k^+(j)}) c_{n+1,j+1,k^+_{floor}} \right] 
+ (1 - p) \left[ \epsilon_{k^-(j)} c_{n+1,j-1,k^-_{ceil}} + (1 - \epsilon_{k^-(j)}) c_{n+1,j-1,k^-_{floor}} \right] \right\}, \quad (2)$$

$$n = N - 1, \ldots, 0, j = -n, -n + 2, \ldots, n, k \text{ is an integer between } -\frac{n}{\rho} \text{ and } \frac{n}{\rho}, k^\pm(j) \text{ are given by Eq. (i) while}$$

$$\epsilon_{k^\pm(j)} = \frac{\ln A_{k^\pm(j)}^{n+1} - \ln A_{k^\pm(j)}^{n+1}}{\Delta Y}. \quad (3)$$
Terminal Payoff

The final condition is

\[ c_{j,k}^N = \max(S_j^N - A_k^N, 0) = \max(S_0 e^{j\Delta W} - S_0 e^{k\Delta Y}, 0), \quad j = -N, -N + 2, \ldots, N, \]

and \( k \) is an integer between \(-\frac{N}{\rho}\) and \( \frac{N}{\rho} \).

The upper (lower) bound of arithmetic averaging values can be deduced by assuming upward (downward) moves of the stock price at all time steps. We can then deduce the range of values that can be assumed by \( k \).
In summary, we compute the updated arithmetic average values based on $n$, $A^n_k$ and $S^{n+1}_{j±1}$.

\[
A^n_k \rightarrow A^{n+1}_{k±(j)} \quad \text{when} \quad S^n_j \rightarrow S^{n+1}_{j±1}
\]
\[
A^n_k \rightarrow A^{n+1}_{k(−(j))} \quad \text{when} \quad S^n_j \rightarrow S^{n+1}_{j−1}
\]

Note that $k$ is an integer while $k±(j)$ and $k−(j)$ are in general non-integers. Since the numerical call option values at the $(n+1)^{th}$ time step are known at integer value of the index $k'$ for $A^{n+1}_{k'}$, we use the interpolation scheme to estimate $c^{n+1}_{j,k±(j)}$ as follows:

\[
c^{n+1}_{j,k±(j)} = \epsilon_{k±(j)} c^{n+1}_{j,\text{floor}(k±(j))} + (1 − \epsilon_{k±(j)}) c^{n+1}_{j,\text{ceil}(k±(j))},
\]

where

\[
\epsilon_{k±(j)} = \frac{\ln A^{n+1}_{k±(j)} - \ln A^{n+1}_{\text{floor}(k±(j))}}{\Delta Y}.
\]

Using the discounted expectation approach, we have

\[
c^n_{j,k} = \left[p c^{n+1}_{j+1,k+(j)} + (1 − p) c^{n+1}_{j−1,k−(j)}\right] e^{−r \Delta t}.
\]
Recall that $S_{n+1}^j = S_0e^{j\Delta W}$ and $A_{n+1}^k = S_0e^{k\Delta Y} = S_0e^{k\rho\Delta W}$. Also, $A_n^k$ becomes $A_{k+}^n$ when $S_n^j \to S_{n+1}^j$ and $A_{k-}^n$ when $S_n^j \to S_{n-1}^j$.

At each time step, we compute the numerical option values at all possible integer values of $k$. 
Remarks

1. When dealing with the discretely monitored Asian options, we only update the values of \( k \) at a time step that corresponds to a monitoring instant. At a time step that does not correspond to a monitoring instant, we compute \( c_{j,k}^n \) using the binomial formula:

\[
c_{j,k}^n = [pc_{j+1,k}^{n+1} + (1 - p)c_{j-1,k}^{n+1}]e^{-r\Delta t}.
\]

2. At the first few time steps, the number of possible averaging values can be smaller than the fixed number of possible values for \( k \) as specified by the quantification approach, where \( \frac{n}{\rho} \leq k \leq \frac{n}{\rho} \). This may appear to pose a paradox. For the convenience of writing the programming code, we may adopt the same quantification approach at the first few time steps. We may argue as follows: under the continuous model, the averaging values is continuous so the number of possible averaging values should not be limited by the discrete lattice tree evolution of the stock price.
3. Extension to Asian options on geometrical averaging of asset values

\[ \ln G_n = \frac{1}{n+1} (\ln S_0 + \ldots + \ln S_n) \]

\[ \ln G_{n+1} = \frac{1}{n+2} (\ln S_0 + \ldots + \ln S_n + \ln S_{n+1}), \]

so

\[ (n + 2) \ln G_{n+1} - (n + 1) \ln G_n = \ln S_{n+1} \]

\[ G_{n+1} = (G_n)^{\frac{n+1}{n+2}} (S_{n+1})^{\frac{1}{n+2}}. \]

Suppose we write

\[ A_k^n = A_0^0 e^{k \Delta Y} = S_0 e^{k \rho \Delta W} \]

\[ S_{j \pm 1}^{n+1} = S_0 e^{(j \pm 1) \Delta W}, \]

we deduce that

\[ e^{k^{\pm}(j) \rho \Delta W} = (e^{k \rho \Delta W})^{\frac{n+1}{n+2}} (e^{(j \pm 1) \Delta W})^{\frac{1}{n+2}}. \]

This gives \( k^{\pm}(j) = g(n, k, j \pm 1) = k^{\frac{n+1}{n+2}} + \frac{j^{\pm 1}}{\rho} \frac{1}{n+2}. \)
Alpha quantile option

The $\alpha$-quantile option takes the barrier level to be a stochastic state variable that defines the terminal payoff.

For a given percentile $\alpha$, $0 \leq \alpha \leq 1$, the $\alpha$-percentile of $\{S_t\}_{t \in [0,T]}$ is defined as

$$B_{\text{inf}}(T; \alpha) = \inf \left\{ B : \frac{1}{T} \int_0^T 1_{\{S_t \leq B\}} dt \geq \alpha \right\}. \quad (A)$$

We gradually lower the barrier $B$ and eventually the percentage of time that $S_t$ stays at or below $B$ just hits at $\alpha$. In other words, $B_{\text{inf}}(T; \alpha)$ is the barrier level such that the asset price $S_t$ is at or below $B_{\text{inf}}(T; \alpha)$ exactly $\alpha$ of the monitoring period. When $\alpha = 0.5$, $B_{\text{inf}}(T; 0.5)$ is the median $S_{\text{median}}$ of the asset price process over the time period $[0, T]$. 
• The asset price is below $S_{median}$ exactly half of the time period $[0, T]$.

• $B_{inf}(T; 1)$ is the realized maximum asset price over $[0, T]$ since the asset price is below this barrier level (infimum among all barrier levels) 100% of the time period.
For a European $\alpha$-quantile call option, the terminal payoff is given by

$$V_\alpha(S, T) = \max(B_{\text{inf}}(T; \alpha) - X, 0),$$

where $X$ is the strike price.

- In the discrete trinomial tree model with $N$ time steps, we write $S_j^N$ as the discrete terminal asset price at maturity, $j = -N, -N + 1, ..., N$. We assume that the possible values taken by the stochastic variable $B_{\text{inf}}$ are limited to $S_j$, $j = -N, ..., N - 1, N$; $S_j = S_0u^j$, where $u$ is the up-jump parameter. One may adopt a finer resolution of the discrete values that can be taken by $B_{\text{inf}}$ for better accuracy.

- The numerical approximate value of the continuously monitored European $\alpha$-quantile call option is given by

$$V_\alpha(S, 0) = e^{-rT} \sum_{j=-N}^{N} P[B_{\text{inf}} = S_j] \max(S_j - X, 0), \ S_j = S_0u^j.$$
Binary cumulative options

Let $V_{\text{cum}}^{\text{bin}}(\alpha, B)$ denote the value of a binary option that pays $1$ at maturity $T$ if the cumulative time staying at or below the down-barrier $B$ is less than $\alpha$ of the total life of the option, $0 \leq \alpha \leq 1$; otherwise the terminal payoff of the option is zero. This option value is equivalent to the state price of the following event:

$$
\frac{1}{T} \int_0^T 1\{S_t \leq B\} dt < \alpha.
$$

For a fixed value of $\alpha$, the payoff of this binary option is $1$ (corresponding to the occurrence of the above event) only if the specified down-barrier $B$ is below the realized value of $B_{\text{inf}}(T; \alpha)$. If otherwise, suppose $B \geq B_{\text{inf}}(T; \alpha)$, according to eq.(A), then $\frac{1}{T} \int_0^T 1\{S_t \leq B\} dt \geq \alpha$, a contradiction to the fact that the above event occurs.
In the discrete world of the trinomial tree, we choose $B = S_j$ for some $j$. We then have

$$V_{\text{cum}}^{\text{bin}}(\alpha, S_j) = e^{-rT}P[B_{\text{inf}} > S_j]$$

so that

$$e^{-rT}P[B_{\text{inf}} = S_j] = e^{-rT}\{P[B_{\text{inf}} > S_{j-1}] - P[B_{\text{inf}} > S_j]\} = V_{\text{cum}}^{\text{bin}}(\alpha, S_{j-1}) - V_{\text{cum}}^{\text{bin}}(\alpha, S_j).$$

The terminal payoff of $V_{\text{cum}}^{\text{bin}}(\alpha, B)$ is given by

$$V_{j,k}^{N} = \begin{cases} 1 & \text{if } 0 \leq k < \alpha N \\ 0 & \text{if } k \geq \alpha N \end{cases},$$

where $k$ counts the number of time steps that $S_{j,i}^n \leq B$ and $N$ is the total number of time steps in the lattice tree calculations. Note that the terminal payoff is independent of $j$ (the index for stock price) since the payoff of the binary cumulative option is independent of stock price.
Numerical Option Values of Continuously Monitored Alpha Quantile Call Option

Parameter values: $\alpha = 0.8$, $S = 100$, $X = 95$, $r = 0.05$, $q = 0$, $\sigma = 0.2$ and $T = 0.25$. 
Accumulators

- Entails the investor entering into a commitment to purchase a fixed number of shares per day at a pre-agreed price (the “Accumulator Price”). This Price is set (typically 10-20%) below the market price of the shares at initiation. This is portrayed as the “discount” to the market price of the shares.

Example

Citic Pacific entered into an Australian dollar accumulator as hedges “with a view to minimizing the currency exposure of the company’s iron ore mining project in Australia”. The company benefits from a strengthening in the A$ above A$1 = US$0.87.
Citic Pacific’s bitter story

- Citic Pacific signed an accumulator that not only set the highest gains but failed to include a floor for losses. The Australian dollar’s value was rising when the contract was signed.

- After July, 2008, the AUD’s value against the USD declined, sliding as low as 1 to 0.65. This slide contributed to HK$800 million loss when the company terminated leveraged foreign exchange contracts between July 1 and October 17.
• The firm also said its highest, marked-to-market loss could reach HK$14.7 billion. Some analysts say if the AUD falls to 1 to 0.50 USD, the mark-to-market loss would rise to HK$26 billion.

• Citic Pacific shares fell 80% on the Hong Kong exchange to HK$5.06 a share on October 24, compared with HK$28.20 a share July 2.

• The company was driven by a “mixture of greed and a gambling mentality” to use the accumulator. Why not simply buy the less risky currency futures to hedge the iron ore mining project?
Cap on upside gain

If the market price of the shares rises above a pre-specified level (“Knock-Out price”) then the obligation to purchase shares ceases. This Price is set (typically 2% to 5%) above the market price of the shares at initiation.

Intensifying downside losses (“I will kill you later”)

If the market price falls below the Accumulator Price (10-20% below the market price at initiation), then the investor would be obligated to purchase more shares. This is called the Step-Up feature. The Step-Up factor can be 2 or up to 5.

- Margin is required to minimize counterparty risks. The investor generally benefits where the share prices remain relatively stable, preferably between the Knock Out Price and the Accumulator Price.
Example of an accumulator on China Life Insurance Company

- **Stock Price Movement of China Life Insurance Company Limited (June 12, 2009 - July 13, 2009)**

![Diagram of Stock Price Movement](image)
**SGD-Equity Accumulator Structure**

Underlying Shares: SEMBCORP INDUSTRIES LTD

Start Date: 05 November 2007

Final accumulation Date: 03 November 2008

Maturity Date: 06 November 2008
(subject to adjustment if a Knock-Out Event has occurred)

Strike Price: $4.7824
Knock-Out Price: $6.1425

Knock-Out Event: A Knock-Out Event occurs if the official closing price of the Underlying Share on any Scheduled Trading Day is greater than or equal to the Knock-Out Price. Under such event, there will be no further daily accumulation of Shares from that day onward. The aggregate number of shares accumulated will be settled on the Early Termination Date, which is the third business day following the occurrence of Early Termination Event.
Shares Accumulation:

On each Scheduled Trading Day prior to the occurrence of Early Termination Event, the number of shares accumulated will be

1,000 when Official Closing Price for the day is higher than or equal to the Strike Price

2,000 when Official Closing Price for the day is lower than the Strike Price

Monthly Settlement Date:

The Shares accumulated for each Accumulation Period will be delivered to the investor on the third business day following the end of each monthly Accumulation Period

Total Number of Shares:

Up to the maximum of 500,000 shares
Accumulation Period and Delivery Schedule

12 accumulation periods in total

<table>
<thead>
<tr>
<th>Accumulation Period</th>
<th>Number of days</th>
<th>Delivery Date</th>
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</thead>
<tbody>
<tr>
<td>05 Nov 07 to 03 Dec 07</td>
<td>20</td>
<td>06 Dec 07</td>
</tr>
<tr>
<td>04 Dec 07 to 02 Jan 08</td>
<td>19</td>
<td>07 Jan 08</td>
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<tr>
<td>03 Jan 08 to 04 Feb 08</td>
<td>23</td>
<td>11 Feb 08</td>
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<tr>
<td>05 Feb 08 to 03 Mar 08</td>
<td>18</td>
<td>06 Mar 08</td>
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<tr>
<td>04 Mar 08 to 02 Apr 08</td>
<td>21</td>
<td>07 Apr 08</td>
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<tr>
<td>03 Apr 08 to 02 May 08</td>
<td>21</td>
<td>06 May 08</td>
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<tr>
<td>05 May 08 to 02 Jun 08</td>
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<tr>
<td>03 Oct 08 to 03 Nov 08</td>
<td>21</td>
<td>06 Nov 08</td>
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</table>
Let $V(j, \ell, i, k)$ denote the value of the accumulator at the $j^{th}$ accumulation period, $\ell^{th}$ business date ($\ell^{th}$ time step if the time step is taken to be one business day), $i^{th}$ stock price level, and $k$ units of shares accumulated in the $j^{th}$ period up to the $\ell^{th}$ day.

- 04 Dec 07 corresponds to the first day in the second accumulation period, so $\ell = 1, j = 2$; 02 Oct 08 corresponds to the 21st day in the 11$^{th}$ accumulation period, so $\ell = 21, j = 11$.

- The last day of the $j^{th}$ accumulation period can be considered as the $0^{th}$ day of the $(j + 1)^{th}$ accumulation period.
An accumulator as a portfolio of occupation time derivatives

- Without the “intensifying loss” feature, the product is like a portfolio of forward contracts with the knock-out feature. Purchases are conditional on survival until the date of accumulation of shares.

- The “intensifying loss” feature can be considered as a portfolio of forward contracts with the “excursion time” feature. The accumulated amount of shares depends on the total excursion time of the stock price staying below the strike price, again conditional on survival until the date of accumulation of share.

In other words, one has to count the number of days that the stock price stays below the strike price, conditional on “no knock-out”.
Numerical scheme

1. Use the forward shooting grid technique to keep track of the total number of shares to be purchased. The grid function is defined by

\[ G(k, i) = k + 2,000 \mathbf{1}_{\{i \leq I_{\text{strike}}\}} + 1,000 \mathbf{1}_{\{i > I_{\text{strike}}\}}. \]

Here, \( I_{\text{strike}} \) is the index that corresponds to the strike price. We set \( I_{\text{strike}} \) such that \( S_0 u^{I_{\text{strike}} + \frac{1}{2}} \) is the actual strike price.

Suppose we take \( m \) time steps per each business day, \( m \geq 1 \); and let \( \ell \) denote the number of time steps lapsed from the last settlement date. For those time steps that do not correspond to the time of stock accumulation, we have the usual binomial scheme:

\[ V(j, \ell, i, k) = e^{-r \Delta t}[pV(j, \ell + 1, i + 1, k) + (1 - p)V(j, \ell + 1, i - 1, k)]; \]

while at a time step that corresponds to stock accumulation, we have

\[ V(j, \ell, i, k) = e^{-r \Delta t}[pV(j, \ell + 1, i + 1, G(k, i + 1)) + (1 - p)V(j, \ell + 1, i - 1, G(k, i - 1))]. \]
2. Jump conditions are applied across each settlement date.

- Right after the settlement of the accumulated shares, $k$ is reset to zero. Right before delivery, compute the value function for all possible values of $k$. If there are $\ell_{\text{max}(j)}$ days in the $j^{\text{th}}$ period, then $k$ assumes values from $1,000 \times \ell_{\text{max}(j)}, 1,000 \times [\ell_{\text{max}(j)} + 1], \cdots, 2,000 \times \ell_{\text{max}(j)}$.

- The jump in the accumulator value across each settlement date is the value of the accumulated units of stock on the settlement date. Moving from the $j^{\text{th}}$ period to the $(j+1)^{\text{th}}$ period, the value of the accumulator is split into the continuation value of the accumulator with $k$ being reset to zero and the value of the stocks transacted. We have

$$V(j, m, \ell_{\text{max}(j)}, i, k) = V(j + 1, 0, i, 0) + k(S_i - X e^{-rM\Delta t}).$$

Here, $M$ is the number of time steps between the settlement date and delivery date.
When $S_{i+1}^{n+1}$ is above the knock-out price, knock-out event occurs and the value of the accumulator becomes $g(k, i + 1) \left( S_{i+1}^{n+1} - X e^{-rM\Delta t} \right)$. Suppose the stocks are delivered 3 days after the settlement date, then $M = 3m$, where $m$ is the number of time steps for each business date.
**Decomposition of an accumulator under immediate settlement**

Under the assumption of monitoring of the upper knock-out barrier on each business date and immediate settlement of the accumulated stock, one can decompose an accumulator into a portfolio of up-and-out barrier call and put options.

The payoff on the observation date $t_i$ is given by

$$
\begin{cases}
0 & \text{if } \max_{0 \leq \tau \leq t_i} S_\tau \geq H \\
S_{t_i} - K & \text{if } \max_{0 \leq \tau \leq t_i} S_\tau < H \text{ and } S_{t_i} \geq K \\
2(S_{t_i} - K) & \text{if } \max_{0 \leq \tau \leq t_i} S_\tau < H \text{ and } S_{t_i} < K,
\end{cases}
$$

where $K =$ strike price and $H =$ upper knock-out level.

- Under delay settlement, the strike price $K$ is paid $\delta$ periods later while the decision criterion on the delivery of one or two stocks is determined by $S_{t_i} \geq K$ or otherwise.
For simplicity, we assume continuous monitoring of the upper knock-out barrier $H$.

- $n =$ total number of observation dates
- $c_{uo} =$ up-and-out barrier call option
- $p_{uo} =$ up-and-out barrier put option

Fair value of an accumulator $= \sum_{i=1}^{n} c_{uo}(t_i; K, H) - 2p_{uo}(t_i; K, H)$.

- When $S_{t_i} \geq K$, the $t_i$-maturity put option is out-of-the-money and the $t_i$-maturity call option has the payoff $S_{t_i} - K$.

- When $S_{t_i} < K$, the call option is out-of-the-money and the put option becomes in-the-money with payoff $K - S_{t_i}$. When the two put options are in short position, the payoff is $-2(K - S_{t_i}) = 2(S_{t_i} - K)$.
Numerical example [taken from “Accumulator Pricing” by K. Lam et al. (2009)]

One-year tenor, 21 trading days in each month, $n = 252$, $H = $105. The initial stock price $S_0$ is $100$, quantity bought on each day is either 1 or 2 depending on the stock price staying above the down-region or otherwise.

- Since the accumulator parameters are designed so that it has a near zero-cost structure, the fair price for the sample accumulator is typically small.
The parameter values are: $S_0 = 100$, $H = 105$, $r = 0.03$, $q = 0.00$, $\sigma = 20\%$. For a zero-cost accumulator with monthly settlement to be fairly priced, a fair discounted purchase price is shown to be 89.32.
**Implied Volatility**

Options’ implied volatility is the volatility implied by the market price of the options based on a pricing model. In other words, given a particular pricing model, it is the volatility that yields a theoretical option value equal to the market price.

<table>
<thead>
<tr>
<th>Barrier Level</th>
<th>Discounted Strike Price K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td>107</td>
<td>36.06%</td>
</tr>
<tr>
<td>105</td>
<td>34.63%</td>
</tr>
<tr>
<td>103</td>
<td>33.10%</td>
</tr>
</tbody>
</table>

For a fixed value of $K$, the implied volatility value is higher for a higher barrier level. For a fixed barrier level, the implied volatility is a decreasing function of the strike price $K$. 
• Given that the accumulator is a zero-cost structure, we compute the volatility that makes the fair price equal to zero.

• Suppose an investor anticipates a volatility of 25% in the future one year. This investor will find the barrier-strike combination in the upper left corner (bold area in Table) favorable because the implied volatilities in those cells have implied volatility larger than 25%.

• The investor should be compensated with a higher barrier level and/or lower purchase price at a higher volatility level since she is shorting two puts.
Value at risk analysis

- Profit/loss distribution is highly asymmetric.

Probability distribution of profit and loss of the sample accumulator
• It has a long left tail meaning that extreme loss is possible.

• Extreme profit is unlikely as the distribution has a short right tail. This is because the contract will be knocked out once the stock price breaches the upper barrier $H$.

• For the sample accumulator contract analyzed, the lower 5-percentile is $-2424.50$. This means that at the maturity of the contract, there is a 5% chance to run a loss more than $2424.50$.

• For the seller of the contract, we can estimate his/her corresponding loss using the same confidence level 0.95. Computation result shows that the value at risk at maturity is $841.01$ with 95% confidence. Noting the two values at risk, we can conclude that the seller runs a much smaller risk than the buyer.
Greek values calculations \((S_0 = 100, \ H = 105, \ K = 90, \ r = 0.03, \ q = 0, \ \sigma = 0.2, \ n = 252)\)

<table>
<thead>
<tr>
<th>Spot price (S)</th>
<th>88</th>
<th>92</th>
<th>96</th>
<th>100</th>
<th>104</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta</td>
<td>290.12</td>
<td>211.95</td>
<td>137.19</td>
<td>65.98</td>
<td>-3.54</td>
</tr>
<tr>
<td>Vega</td>
<td>-12139</td>
<td>-12507</td>
<td>-11182</td>
<td>-8072</td>
<td>-2966</td>
</tr>
</tbody>
</table>

Immediate settlement of stocks

<table>
<thead>
<tr>
<th>Delay settlement (3 days)</th>
<th>Delta</th>
<th>Gamma</th>
<th>Vega</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>288.05</td>
<td>-18.67</td>
<td>-12201</td>
</tr>
<tr>
<td></td>
<td>209.63</td>
<td>-19.35</td>
<td>-12554</td>
</tr>
<tr>
<td></td>
<td>134.88</td>
<td>-18.16</td>
<td>-11220</td>
</tr>
<tr>
<td></td>
<td>63.48</td>
<td>-17.62</td>
<td>-8100</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>-16.37</td>
<td>-2978</td>
</tr>
</tbody>
</table>

Gamma is the sensitivity of delta to stock price.

Vega is the sensitivity of contract value to volatility.
• Delta, gamma, and vega are all sizable because an accumulator contract is composed of many option contracts with different expiration dates.

• There is an asymmetry in the delta and vega values. When the spot price is low (say $S = 88$), the magnitude of delta and vega values are much larger than those when the spot price is high (say $S = 104$).

• Delta values are decreasing function of $S$ because gamma values remain at a negative level. Delta has a magnitude of 288.05 (delay settlement) when $S = 88$, but its magnitude drops to $-6.47$ when $S = 104$. This means that losing buyers will be more vulnerable to price changes than winning buyers.
• Vega has a magnitude of 12201 when $S = 88$, but drops to a magnitude of 2978 when $S = 104$ meaning that compared to winning buyers, losing buyers are more vulnerable to volatility changes as well. This may be one reason why some buyers of the contract become very desperate when the market turns south in recent months.

• This asymmetry is consistent with the finding that the value at risk of the buyer is several times that of the seller.